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By D. Davis

Technical Note

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Engineering Command

# THE EFFECTS OF HIGH TEMPERATURE ON STRUCTURAL CONCRETE IN NAVY FIREFIGHTING TRAINING FACILITIES

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**ABSTRACT** An investigation was completed on the effects of high operational temperatures on a Navy firefighting training facility at the Naval Training Center, Mayport, Florida. Concrete temperature measurements were made during a simulated maximum use training cycle, core samples were retrieved and examined, and predictions of concrete thermal performance were made with a finite element model. It was concluded that the concrete had not deteriorated and should perform well for years of additional service. Refractory linings are not required for new facilities if these facilities are constructed of heat resistant, high strength lightweight concrete and the walls and ceiling near the fire source are protected by a continuous steel plate barrier.

93-18007



NAVAL CIVIL ENGINEERING LABORATORY PORT HUENEME CALIFORNIA 93043-4328

# METRIC CONVERSION FACTORS

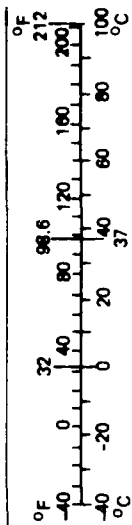
## Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
<b>LENGTH</b>				
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
<b>AREA</b>				
in <sup>2</sup>	square inches	6.5	square centimeters	cm <sup>2</sup>
ft <sup>2</sup>	square feet	0.09	square meters	m <sup>2</sup>
yd <sup>2</sup>	square yards	0.8	square meters	m <sup>2</sup>
mi <sup>2</sup>	square miles	2.6	square kilometers	km <sup>2</sup>
	acres	0.4	hectares	ha
<b>MASS (weight)</b>				
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
<b>VOLUME</b>				
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft <sup>3</sup>	cubic feet	0.03	cubic meters	m <sup>3</sup>
yd <sup>3</sup>	cubic yards	0.76	cubic meters	m <sup>3</sup>
<b>TEMPERATURE (exact)</b>				
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

\*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price \$2.25, SD Catalog No. C13.10-286.

## Approximate Conversions from Metric Measures

When You Know	Multiply by	To Find	Symbol
<b>LENGTH</b>			
millimeters	0.04	inches	in
centimeters	0.4	inches	in
meters	3.3	feet	ft
meters	1.1	yards	yd
kilometers	0.6	miles	mi
<b>AREA</b>			
square centimeters	0.16	square inches	in <sup>2</sup>
square meters	1.2	square yards	yd <sup>2</sup>
square kilometers	0.4	square miles	mi <sup>2</sup>
hectares (10,000 m <sup>2</sup> )	2.5	acres	
<b>MASS (weight)</b>			
grams	0.035	ounces	oz
kilograms	2.2	pounds	lb
tonnes (1,000 kg)	1.1	short tons	
<b>VOLUME</b>			
milliliters	0.03	fluid ounces	fl oz
liters	2.1	pints	pt
liters	1.06	quarts	qt
liters	0.26	gallons	gal
cubic meters	35	cubic feet	ft <sup>3</sup>
cubic meters	1.3	cubic yards	yd <sup>3</sup>
<b>TEMPERATURE (exact)</b>			
Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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## INTRODUCTION

Navy firefighting training facilities are subject to repeated cycles of high temperature shipboard fire simulations. These portland cement concrete structures must be protected from deleterious thermal effects. This can be achieved by using either protective steel panels or an outer layer of refractory concrete. During shakedown testing of a new training facility at the Naval Submarine Base, New London, Connecticut, a large section of refractory concrete spalled. Subsequent inspection and testing by a refractory consultant led to the conclusion that the installed refractory system was adequate for the intended service. The spalling incident was a result of the "unusually hostile environment created during the testing session...which was not at all representative of standard operating environments during fire training sessions."<sup>1</sup> Due to specification conflicts and drawings which did not indicate where to install the coating, refractory linings were eliminated from the training facilities at the Naval Training Center (NTC), Mayport, Florida. Instead, steel panels were attached to the inside surface of the walls which are exposed to the highest thermal loading.

The Naval Civil Engineering Laboratory (NCEL), as part of the Naval Facilities Engineering Command (NAVFAC) sponsored Engineering Investigation Program, was tasked to evaluate the thermal performance of the structural concrete at Mayport. Tasks included a visual assessment of current concrete condition, identification of those facilities experiencing maximum thermal loadings, petrographic examination of selected concrete cores, and temperature measurements during simulated maximum use cycles. The results from test data and analytical predictions of concrete performance could then be used to determine if portland cement concrete, adequately protected by steel panels, was a viable alternative to the more costly approach of protecting structural concrete with an outer layer of refractory material.

This report documents the NCEL firefighting training facility investigation. It begins with a summary of a preliminary site visit which the evaluation team made to NTC, Mayport. This visit led to a consensus as to which facility was critical and how that facility should be tested. A test plan evolved that included locations for temperature gauges and concrete core samples, and the testing cycle required to simulate maximum facility use. This report then addresses details of the final test preparations, which include instrumentation installation and core removal, and the actual thermal cycling test. Results from the testing in the form of temperature/time histories and petrographic evaluation of the core samples are presented along with analytical predictions of concrete thermal behavior. This report concludes with a summary of the investigation findings, conclusions, and recommendations.

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<sup>1</sup>N.E. Heard. A Refractory Insulation Study, Firefighting Training Facilities, U.S. Naval SUBASE/Groton, CT, InSpec/USA, Houston, TX, 15 Dec 1989.

## **PRELIMINARY TEST PREPARATION**

### **Site Visit**

A team from NCEL and the Atlantic Division of NAVFAC visited NTC, Mayport, on 18 April 1991 to inspect the firefighting training facilities. The purpose of this visit was to identify which training facility was experiencing the highest temperature (hence the most likely to undergo degradation due to excessive heat exposure), and to gather data useful for planning temperature gauge and concrete core sample extraction locations. After touring the various training facilities (which were operated for the inspection team), consulting with training personnel at NTC, and analyzing the results from a hand-held pyrometer, it was determined that training facilities 19F3-B3 and 19F3-B4 were experiencing the hottest operating temperatures. Not only do these two identical facilities sustain the largest fire, they also have the highest rate of usage: up to 40 training cycles a day compared to 4 to 5 cycles for the other trainers.

It was agreed that NCEL should instrument and test training facility 19F3-B4 (Building 1803) and subject it to 40 burn cycles. Thermocouples would be concentrated on the back (south) wall of 19F3-B4 due to the proximity of that wall to the fire source. A preliminary inspection suggested that 11 concrete core samples should be extracted. NCEL agreed that all core openings would be properly plugged so that future operation of the facility would be unaffected.

### **Description of Training Facility**

The large size and configuration of training facility 19F3-B4 presented several challenges for the evaluation team (Figure 1). The propane fuel fire is generated in a central fireplace compartment which measures 25 by 13 feet in plan and has a ceiling height of 30 feet (Figures 2 and 3). A roofed, elevated staging area provides a platform from which trainees advance toward the fire with fire suppression gear. The burner and facility control room is on the other side of the fireplace compartment.

The wall nearest to the fire source (south wall) is protected by a series of 325-pound, 1/4-inch-thick, 3-foot-wide by 8-foot-high steel panels which must be removed to gain access to the concrete underneath. The close fit of the steel panels ensures that the structural concrete wall is protected from direct exposure to the fire. Similar steel panels also protect a portion of the west wall which meets the south wall. All of the remaining interior walls and ceilings of facilities 19F3-B3 and B4 are bare concrete.

### **Selection of Thermocouple Locations**

It was decided to place most of the temperature gauges on the south wall of the fireplace compartment along a vertical line closest to the fire source, thus ensuring that the maximum temperature in the facility would be recorded. It should be noted from Figure 4 that each steel plate is suspended from two hooks which are anchored into the concrete. This suggests the potential for a direct heat path from the exposed steel plates to the concrete underneath. This consideration and the desirability of having gauges located near the ceiling and at an elevation of about 8 feet above the floor (maximum exposure to the fire) led to the following gauge locations:

THERMOCOUPLELOCATION

TC-1	Outside ambient air temperature
TC-2	Concrete ceiling, 1 foot from south wall
TC-3	On the 3/8-inch galvanized steel bolt holding the upper plate bent bar hook
TC-4	On the upper plate bent bar hook
TC-5	On the concrete at the same elevation of TC-4 adjacent to the bent bar hook
TC-6	On the concrete at the same elevation of TC-4 at a distance of 1 inch from the bent bar hook
TC-7	On the upper steel plate at the same elevation as Core 11
TC-8	On the lower steel plate at the same elevation as Core 8
TC-9	On the 3/8-inch galvanized steel bolt holding the lower plate bent bar hook
TC-10	On the lower plate bent bar hook
TC-11	On the concrete at the elevation of TC-10 adjacent to the bent bar hook
TC-12	On the concrete at the elevation of TC-10 at a distance of 1 inch from the bent bar hook
TC-13	On the concrete at the same elevation of TC-10 at a distance of 1 foot from the bent bar hook.
TC-14	Outside ambient air temperature

Gauges TC-1 and TC-14 measure the outside ambient air temperature. Readings from these gauges will indicate if the remaining gauges are being affected by events other than true temperature changes due to facility operation.

Gauge TC-2 is in direct contact with the exposed concrete ceiling, 1 foot away from the south wall. This gauge will measure the radiated heat from the fire below as well as the effect from accumulated hot exhaust gases.

Gauges TC-3 and TC-4 are mounted directly on one of the bent bar hooks that support the uppermost steel plate. These gauges will indicate if significant heat transfer occurs between the exposed steel plate and the plate mounting hardware. Gauges TC-5 and TC-6 are mounted

on the concrete at the same elevation as TC4 to measure the concrete temperature. Heat transfer effects, if any, from the hook to the concrete should be detected by these gauges.

Gauges TC-9 through TC-13 are mounted behind the lower plate at an elevation 8 feet above the floor. They are arranged in a pattern similar to those behind the upper plate.

Finally, gauges TC-7 and TC-8 are mounted directly on the upper and lower steel plates.

### **Concrete Core Sample Locations**

During the first site visit, no signs of spalling or other evidence of thermal distress was noted in any of the exposed concrete. There were some surface cracks that appeared to be unplanned construction cold joints rather than damage caused by high temperatures. Core locations were identified that permitted the analysis of concrete from areas exposed to temperatures and from areas subjected to little thermal loading. The latter served as reference cores.

Figures 5 and 6 depict the 4-inch-diameter core locations. The reference cores (1 through 5) are located on the west wall of facility 19F3-B4 at an elevation that places them below the floor of the fireplace compartment. These core locations are not subjected to high temperatures resulting from facility operation.

Cores 6 and 7 are also located in the west wall in line with Core 1, but at an elevation that places them within the fireplace compartment. Core 6 is located at an elevation 6 feet from the floor of the compartment while Core 7 is about 3 feet from the ceiling.

Cores 8 through 11 are located along the center of the south wall in the general location of the temperature gauges. Core 8 is located where the upper steel plate left side hook bolt is anchored to the concrete. This core will be removed with the hook bolt still embedded in the concrete. Core 9 is located adjacent to Core 8, Core 10 is located 12 feet above the floor, and Core 11 will be drilled 3 feet from the ceiling of the fireplace compartment.

A final core, number 12, is located at the same elevation as Core 10, but it is displaced 1 foot to the side. This core opening provides a means for routing the instrumentation leads to the resistance temperature detector which is located outside of the fireplace compartment on the roof of the adjacent burner room.

### **Contracts for Petrographics Analysis and Test Support**

Prior to the test, a contract was awarded to Construction Technology Laboratories (CTL), Incorporated, in Skokie, Illinois to conduct concrete physical property tests and petrographic examinations of the concrete core samples. Physical property tests are needed to determine the type of concrete in the facility and to provide data for use in a finite element model for predicting concrete thermal behavior. Results from the petrographic examinations will indicate if the concrete has experienced any degradation due to thermal effects.

An additional contract was awarded to a local contractor to provide test support services. These services included:

1. Removing the four steel panels along the centerline of the south wall of the fireplace compartment.
2. Extracting the concrete cores and patching the holes with cement mortar.



3. Packaging the eleven cores and shipping them to CTL, Incorporated, for analysis.
4. Replacing the steel panels.

## FINAL TEST PREPARATION AND TEST EXECUTION

### Core Extraction

The NCEL test team arrived at NTC, Mayport on Monday, 9 September 1991. All final test preparations, test execution, and cleanup had to be completed by the end of the week so that the facility would be available for training the following week. The test support contractor had arrived the previous Friday and had already removed the four steel panels that protect the south wall. This was accomplished by bolting a chain fall to the ceiling near the wall and using it to lift each plate, starting with the top plate, free of the bent bar support hooks. This work was facilitated using a scaffold that had been assembled within the compartment.

NCEL engineers inspected the exposed concrete and detected no obvious degradation due to the thermal loading. Some discoloration was evident and was assumed to be carbon resulting from combustion products.

The contractor was allowed to proceed with core removal (Figure 7). No unusual problems were encountered and, as was expected, some of the cores contained pieces of steel reinforcement. Each core was tagged with its identification number and placed in a protective plastic bag. The 11 bagged cores were then placed in a wooden crate for shipping to CTL (Figure 8). The core openings were plugged with a *super plasticized, nonshrinking expansive* grout. This material was easily mixed in small batches and was hand tamped into the wall openings (Figure 9).

### Instrumentation Installation

Two types of thermocouples were used to measure temperatures in training facility 19F3-B4. Those used for concrete surface measurements were model RCF manufactured by the NANMAC Corporation. This ribbon contact thermocouple features a flat exposed sensing tip which can be easily mounted onto any flat surface with an appropriate cement. Desirable features of this device include a low millisecond response time, a low thermal mass for minimal disturbance of the local temperature, and the capability of operating in the temperature range expected during the test. Surface bonding was achieved using a thin coating of a magnesia-based adhesive manufactured by Cotronics Corporation. This adhesive was selected for its high temperature limit (3,000°F), room temperature curing, high thermal conductivity, and low electrical conductivity. Washer thermocouples were used for measuring metal surface temperatures. These were attached by fastening them to the steel surfaces with number 4-40 screws. Fused Kapton insulated lead wire, rated for use at temperatures up to 600°F, was attached to each thermocouple.

Thermocouple lead wires were routed to core opening 12 and passed through the wall to the input terminal of the uniform temperature reference (UTR) system positioned on the roof of the burner room. Output wires from the UTR were bundled together and passed down to a terminal board and data acquisition computer stationed at ground level outside the burner room access door. A data acquisition system block diagram is presented in Figure 10.

The test support contractor tamped grout into core opening 12, and was careful not to damage any of the thermocouple lead wires. Then the steel panels were rehung on their support hooks, the chain hoist was removed, and the scaffolding was disassembled. Firefighting training facility 19F3-B4 was ready for testing.

### Temperature Cycling Test

The temperature cycle test was conducted on the morning of 12 September 1991. The operators were instructed to cycle the facility 40 times to simulate a typical training exercise. Each 5-minute cycle consisted of a burn phase of 3 minutes followed by a 2-minute cooling-off period. During each burn, an operator occasionally directed water from a fire hose into the fire-pit. This action prevented automatic burner cutoff controls from activating due to heat buildup.

Selected instrumentation output was monitored graphically on the data computer as the test progressed. At about the 20<sup>th</sup> burn cycle it was apparent that the temperature readings had stabilized and were rising only slightly with each additional run. When one of the propane-fired burners ceased to function after the 28<sup>th</sup> test run, it was decided to end the test. After the test, NTC personnel expressed the opinion that the training facility had been operated at temperature levels which exceeded those experienced during a maximum use training exercise.

## RESULTS OF TESTS AND ANALYSIS

### Temperature-Time Histories

Twenty-eight test runs in training facility 19F3-B4 were completed. All were recorded successfully with the exception of run 3 which was missed due to a computing error. Selected plots of temperature in degrees fahrenheit versus time in seconds are presented in Figures 11 through 14.<sup>2</sup> The transient spikes that appear on the plots are due to radar or other interference and should be ignored when interpreting the data.

At the beginning of the test all of the thermocouples registered temperatures of around 100°F, or slightly higher (Figure 11). Since the ambient air temperature outside the building was about 80°F, the elevated temperatures inside the fireplace compartment were due to the burner pilot fires which had been lit an hour before the start of the test.

Once the pit fire was fully ignited (Figure 11), the thermocouples indicated rising temperatures until the end of the 3-minute burn. On this graph and those that follow, the thermocouple traces tend to cluster in two groups. The group that appears lower on the graphs (traces 2, 9, 10, 11, 12, and 13) are readings from the ceiling gauge and those gauges mounted on the concrete and plate support hardware behind the lower steel plate. The upper group consists of the gauges mounted behind the upper steel plate (traces 3 through 6) and trace 7, which is the output from the thermocouple mounted directly on the upper steel plate. The highest recorded temperatures are from gauge number 8, which is the thermocouple mounted on the lower steel plate.

As the testing proceeded, temperatures continued to rise and the gauge outputs became flatter throughout each 3-minute burn cycle. By the time the 21<sup>st</sup> cycle was reached, however,

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<sup>2</sup>A complete set of temperature plots can be found in Appendix A.

temperature readings from all of the gauges had stabilized at their final, nearly steady state values.

Significant results from this test include the following:

1. Of those gauges mounted directly on the concrete wall, the ones at the upper plate level experienced the highest temperature. The highest temperature recorded was 360°F for gauge 6.
2. The maximum temperature on the ceiling (gauge 2) was 320°F.
3. The concrete at the lower gauging station was subjected to a maximum temperature of 300°F.
4. The maximum recorded temperature from any gauge was 530°F and this was from the thermocouple mounted on the lower steel plate at an elevation 8 feet above the floor. At this level the plate was fully exposed to radiant heating effects from the nearby pit fire.
5. The enhanced flue effect created by welding longitudinal steel channels to the underside of the protective steel panels, thus extending them an additional 1-1/2 inches from the concrete wall, may account for the lower temperatures recorded on the concrete wall behind the lower steel panel.

### **Concrete Core Tests**

**Introduction.** Construction Technology Laboratories (CTL) was tasked to perform petrographic examinations on the six cores which had been subjected to thermal loading during routine training exercises as well as to determine the following physical properties from the reference cores (1 through 5) which had been subjected to minimal thermal loading:

- a. Modulus of elasticity
- b. Coefficient of thermal expansion
- c. Specific heat
- d. Thermal Diffusivity
- e. Thermal conductivity

**Approach.** The petrographic examination was conducted in accordance with ASTM C556-83, "Standard Practice for Petrographic Examination of Hardened Concrete." Two of the six cores which underwent petrographic examination were from the west wall of the firefighting facility and had been exposed to moderate heat; the remaining cores were from the south wall and had been exposed to considerably higher temperatures.

Cores number 4 and 5 were used to determine the modulus of elasticity in accordance with the applicable portions of ASTM C469-87, "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression." Since compressive strength is

required to perform this test, this property was first determined in accordance with ASTM C42-87, "Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete." All test results for modulus of elasticity include the effects of steel reinforcement contained within the cores.

Core number 2 was instrumented with gauge points to measure changes in longitudinal length caused by temperature variations. Length readings taken when the core was cooled, at room temperature, and when heated to 140°F were used in conjunction with a formula to compute the coefficient of linear expansion.

The specific heat from Core number 1 was determined by the methodology described in U.S. Army Corps of Engineers CRD-C124-73, "Method of Test for Specific Heat of Aggregates, Concrete, and other Materials (Method of Mixtures)." The specific heat was determined for material in saturated state, an oven dry state, and as received from Mayport where the material was assumed to have a moisture content of 6 to 8 percent of its oven dry weight.

Thermal diffusivity of Core Number 3 was determined in accordance with U.S. Army Corp of Engineers CRD-C36-T3, "Method of Test for Thermal Diffusivity of Concrete," while thermal conductivity was determined by the methodology described in U.S. Army Corps of Engineers CRD-C44-63, "Method for Calculation of Thermal Conductivity of Concrete." The method for determining thermal conductivity uses the measured properties of thermal diffusivity, specific heat, and unit weight with all properties stated for the same moisture content.

**Results.** The results of the petrographic examination showed the following:

a. The concrete cores consist of siliceous lightweight coarse aggregate (expanded shale) and quartz sand in a portland cement paste. The paste is moderately hard and the paste aggregate bond is tight.

b. Cores 7, 9, 10, and 11 yielded evidence of cold joints with a contact plane approximately parallel to the long axes of the cores. The concrete on either side of the contact plane was generally well bonded.

c. The inside wall end of the cores are blackened. Carbonation and attendant softening of the paste occur to an average depth of 0.15 inch in Cores 6 and 7, and to a depth of 0.3 to 0.4 inch in Cores 6 through 11.

d. No evidence of distress was observed in the concrete around the anchor bracket located in the inside wall end of Core 8. The portion of the anchor embedded in the concrete is slightly corroded, and the anchor is not well bonded to the concrete.

The results of the physical property tests showed the following:

a. Modulus of elasticity: 2,600,000 psi.

b. Compressive strength of two core samples: 6,540 and 6,180 psi.

c. Coefficient of thermal expansion over a temperature range from 50°F to 140°F:  $6.4 \times 10^{-6}$  in./in. per °F.

d. Specific Heat: 0.29 Btu/lb°F for concrete with a moisture content of 16 percent of oven dry weight.

e. Thermal diffusivity: 0.029 ft<sup>2</sup>/hr for concrete with a moisture content of 10 percent of oven dry weight at the end of the test.

f. Thermal conductivity: 11.0 Btu-in./hr-ft<sup>2</sup> °F for concrete with a moisture content of 10 percent of oven dry weight.

The report prepared by CTL, Incorporated, is included as Appendix B to this report.

### Finite Element Analysis

**Introduction.** A two-dimensional finite element model was used to predict the thermal performance of the concrete in the walls of the Mayport training facility. Four noded, axisymmetric linear elastic elements were used, the edges were assumed to be free, and the effects of steel reinforcement were not included. Two cases were considered: a uniform 10-inch-thick wall and a wall with an embedded 3-inch-long, 3/4-inch-diameter anchor bolt located at the center of the wall element anchor.

**Approach.** Concrete properties needed for the analysis were taken from the results of the CTL investigation. These included:

- a. Modulus of elasticity:  $E = 2,600,000 \text{ psi}$
- b. Thermal expansion coefficient:  $\alpha = 6.4 \text{ ppm/°F}$
- c. Conductivity:  $K = 11.0 \text{ Btu-in./(hr-ft}^2 \text{ °F)}$
- d. Specific heat:  $sh = 0.23 \text{ Btu/(lb °F)}$
- e. Compressive strength:  $f'_c = 6,360 \text{ psi}$
- f. Unit weight:  $\gamma = 130 \text{ pcf}$

Assuming that CTL measured the specific heat at 68°F and that this property varies linearly between 0°F and 400°F, the following input was used in the finite element model:

$$sh = 0.0166 \text{ Btu/(in.}^3 \cdot \text{°F)} \text{ at } 0^\circ\text{F}$$

$$sh = 0.0207 \text{ Btu/(in.}^3 \cdot \text{°F)} \text{ at } 400^\circ\text{F}$$

Finally, the concrete tensile strength was assumed to be  $f_t = 420 \text{ psi}^3$ .

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<sup>3</sup>L.J. Malvar and M.E. Hironaka. "Determination of a heat resistant concrete for airfield pavements," Computers and Structures, vol 40, no. 2, Jul 1991, pp 303-311.

Using the field temperature measurements as a guide, it was assumed that the wall temperature increased linearly from ambient temperature to 250°F in 5 minutes, then increased to the maximum measured temperature of 360°F at 25 minutes.

**Results.** Figure 15 shows the third principle stress,  $\sigma_3$ . High compressive stresses (about 3,000 psi) parallel and close to the wall interior face (depth = 0) are observed. Similar compressive stresses, although lower, are observed on the exterior face (depth = 10 inches). These compressive stresses are less than 50 percent of  $f'_c$  and will not affect the integrity of the wall.

Figure 16 shows the first principal stress,  $\sigma_1$ . It is observed that high tensile stresses (in the wall plane) occur in the central part of the wall. These stresses could induce internal cracking perpendicular to the wall plane which would be present everywhere in the wall. This cracking would not propagate to the wall faces during the heating phase because of the compression existing there (as shown in Figure 15). The presence of steel in this zone could relieve these tensions and prevent these cracks altogether.

Tensile stresses on the order of 270 psi are found on the interior wall face (Figure 16). At this location, these tensile stresses are perpendicular to the wall face, indicating a potential for face delamination which would occur within the first half inch if the concrete tensile strength was inadequate. The available tensile strength is about 420 psi, hence no sudden delamination should occur. However, cyclic thermal loading of the wall will propagate microcracks oriented in the wall plane. This was observed experimentally in Cores 10 and 11 at depths of up to 0.2 inch.

Figure 17 shows  $\sigma_3$  around the bolt. Due to the very different conductivity properties, the bolt heats faster and tries to expand laterally and longitudinally. The lateral expansion explains the high compressive stresses at the bolt base (3 inches from the wall face). Due to the triaxial confinement, the available concrete compressive strength appears adequate to sustain the compressive stresses, even the large peak. Just after the end of the bolt, the concrete is in tension, as shown in Figure 18.

Assuming perfect bond between bolt and concrete, the bolt's longitudinal expansion tries to pull out the concrete on the wall's interior face. This is indicated by the high tensile stresses (above 1,000 psi) on the wall's interior face (depth = 0). In practice, a small conical ring may pull out around the bolt, but most likely the bond will be lost within the first half inch and the concrete will not crack.

Steel reinforcement was not modeled in the analysis. Centrally located orthogonal steel meshes would prevent internal cracking. However, if two steel meshes are provided, one close to each face of the wall, an increase in compressive stress may occur in the concrete close to the faces. This will enhance the potential for delamination and will be exacerbated if the cover is small. A small cover (less than 2 inches) would also subject the steel to higher temperatures and would enhance the spalling potential due to the different coefficients of expansion and thermal strain incompatibility.

Additional runs were carried out using a reference temperature of -20°F. The results showed that delamination would occur at the inner wall face. However, delamination would probably not occur if the facility was allowed to be preheated by gradual warmup due to burner pilot fires.

Additional runs were conducted using normal weight concrete. It was shown that for a same value of  $\alpha$ , stresses in the concrete could be up to twice as high. This is due to the higher

modulus of elasticity found in normal weight concrete. Thus, normal weight concrete is a poor choice for this type of application.

## FINDINGS

1. The maximum temperature recorded on the inner surface of the concrete wall of facility 19F3-B4 was 360°F. This occurred at an elevation of 1 foot below the ceiling.

2. The maximum temperature recorded on the steel plate that protects the underlying concrete wall was 530°F. This was at an elevation of 8 feet above the floor of facility 19F3-B4.

3. The steel plating extends an additional 1-1/2 inches from the concrete wall than is indicated on the facility as-built drawings. This was apparently done to create a more efficient flue for dissipating hot exhaust gases.

4. The concrete in the facility has an average compressive strength of 6,360 psi and an average unit weight of 130 pcf. The concrete mix consists of a siliceous lightweight coarse aggregate (expanded shale) and quartz sand in a portland cement paste.

5. Visual observations of the exposed concrete made prior to testing indicated no degradation due to thermal loading. More detailed petrographic analysis of some of the core samples did reveal some minor carbonation and softening of the paste and microcracking of the concrete wall inner surface.

6. The core that contained an exposed steel plate anchor bolt showed no paste softening or carbonation next to the embedded bolt.

## CONCLUSIONS

1. The concrete in facility 19F3-B4 has not deteriorated due to heat and should perform fine for many years of service under the current loading.

2. Analytical results from a finite element model suggest that the failure mechanism having the most potential of occurring is delamination of the concrete interior wall face. However, based on the low rate of microcrack growth parallel to the wall face found in a few core samples, this process, if present, is unlikely to lead to a significant delamination problem.

3. Refractory concrete linings are not required provided that firefighting facilities are constructed of heat resistant, high strength lightweight concrete and the walls and ceiling near the fire source are protected by a continuous steel plate barrier.

## RECOMMENDATIONS

1. All new construction should have a minimum steel reinforcement concrete cover of 2 inches. The outer 1 inch of cover will offer a margin of safety against potential surface softening and cracking and should not be used in determining section properties for structural analysis. Also, the walls and ceiling near the fire source should be protected by a continuous steel plate barrier.

2. A new specification should be implemented for all heat-exposed concrete to be used in new firefighting facility construction. This could be accomplished by amending NFGS-03300D: Cast-in-Place Concrete, or by creating a new guide specification. Recommended concrete properties can be found in Appendix C.

3. Preheating the facility by burner pilot fires at least 30 minutes prior to use should be encouraged to further lessen the potential of concrete delamination.

## ACKNOWLEDGMENTS

The author wishes to thank the following people for their contributions to this investigation:

1. LCDR R. Dolan and STGCS Murray of the Naval Training Facility, Mayport, Florida, for their assistance in planning and conducting the test at facility 19F3-B4.

2. Mr. Doug Burke of NCEL's Material Science Division who selected the concrete core sample locations and provided useful insights into interpreting the results of the petrographic analysis.

3. Dr. Javier Malvar of NCEL's Structures Division who assisted in determining the temperature gauge locations and performed the finite element analysis to predict the concrete thermal performance.

4. Mr. Dan Goff of NCEL's Instrumentation Division who selected the temperature gauges, designed the data recording and retrieval system, installed the instrumentation under difficult working conditions, and obtained the required temperature data.



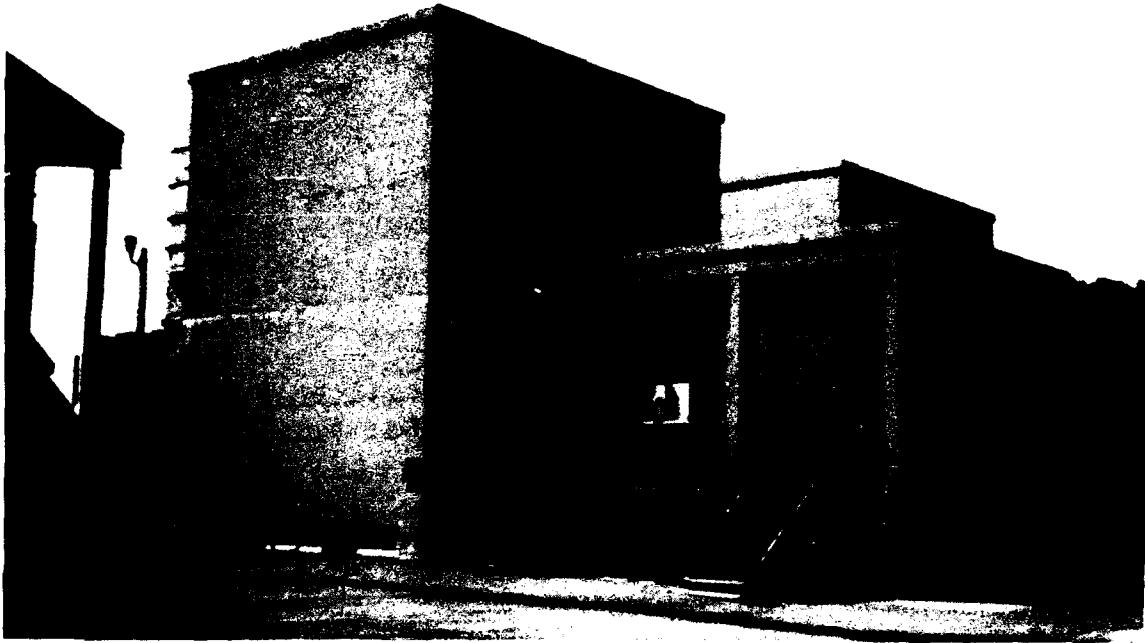


Figure 1

Exterior view of training facility 19F3-B4 at FTC Mayport. The staging area is reached by steel stairways. The fireplace compartment is the large block-like structure to the left of the staging area.

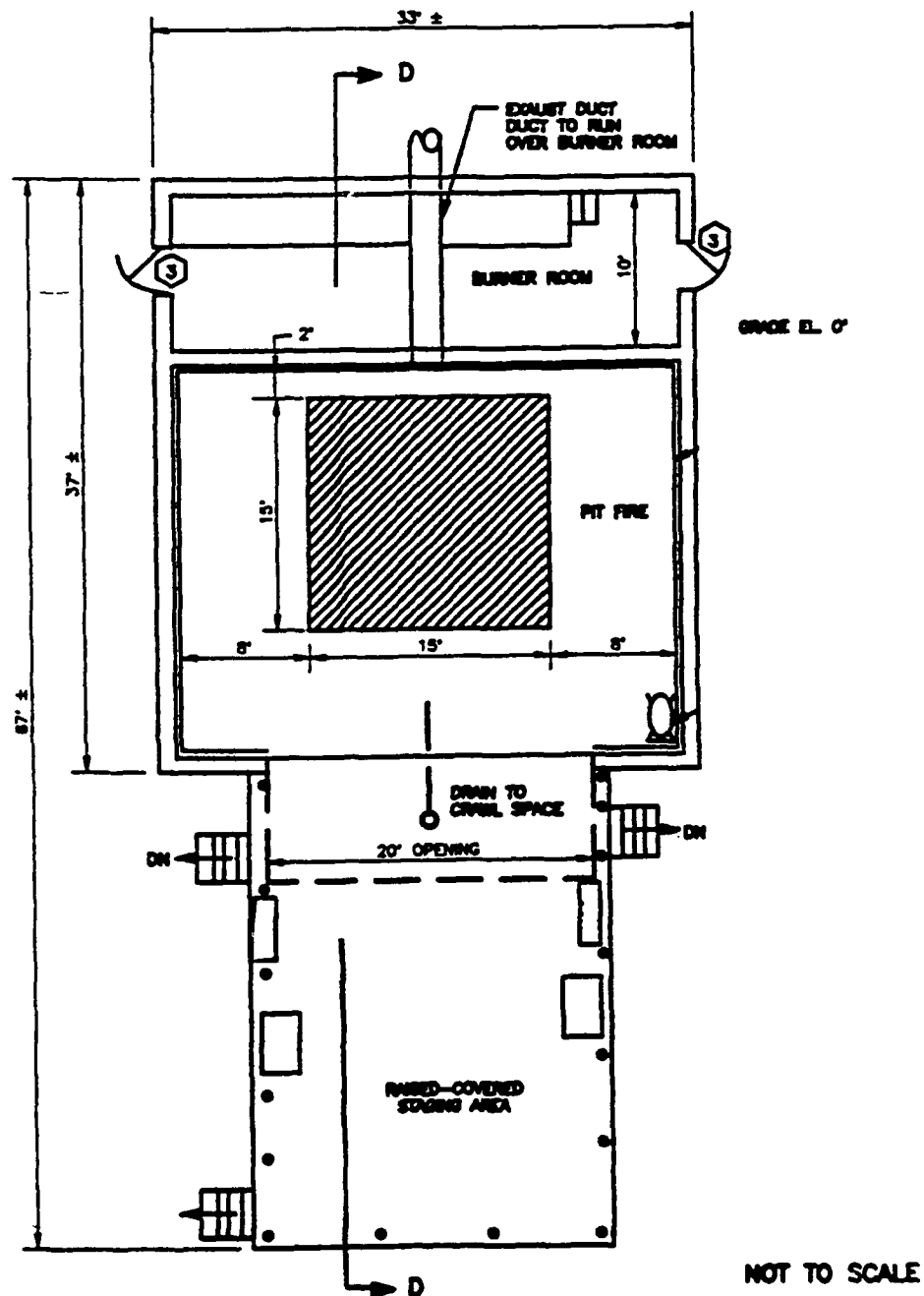
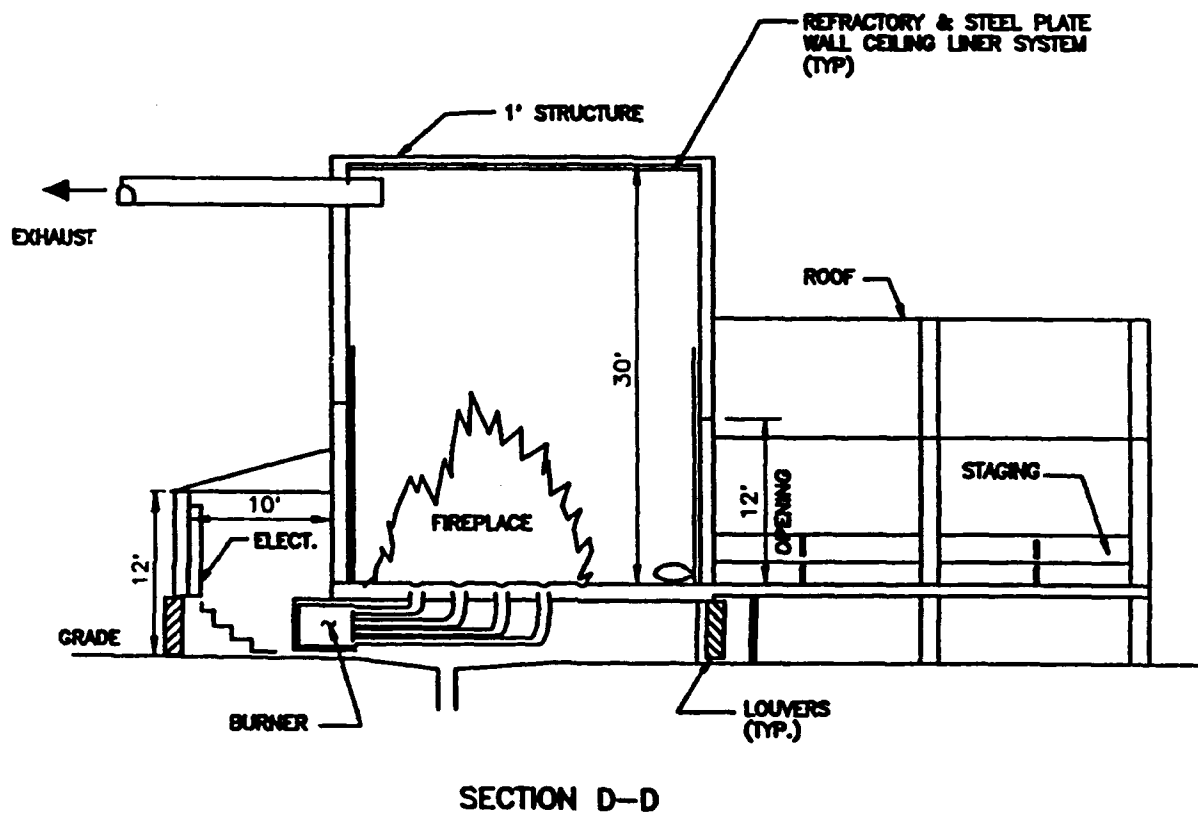


Figure 2  
Plan view of training facility 19F3-B4 from MIL-HDBK-1027/1. Mayport facility lacks the refractory layer and, except for the wall nearest to the pit fire, most of the wall steel plate liner system.



NOT TO SCALE

Figure 3  
Elevation view of training facility 19F3-B4 from MIL-HDBK-1027/1.  
Mayport facility lacks the refractory layer and ceiling steel plate liner system.

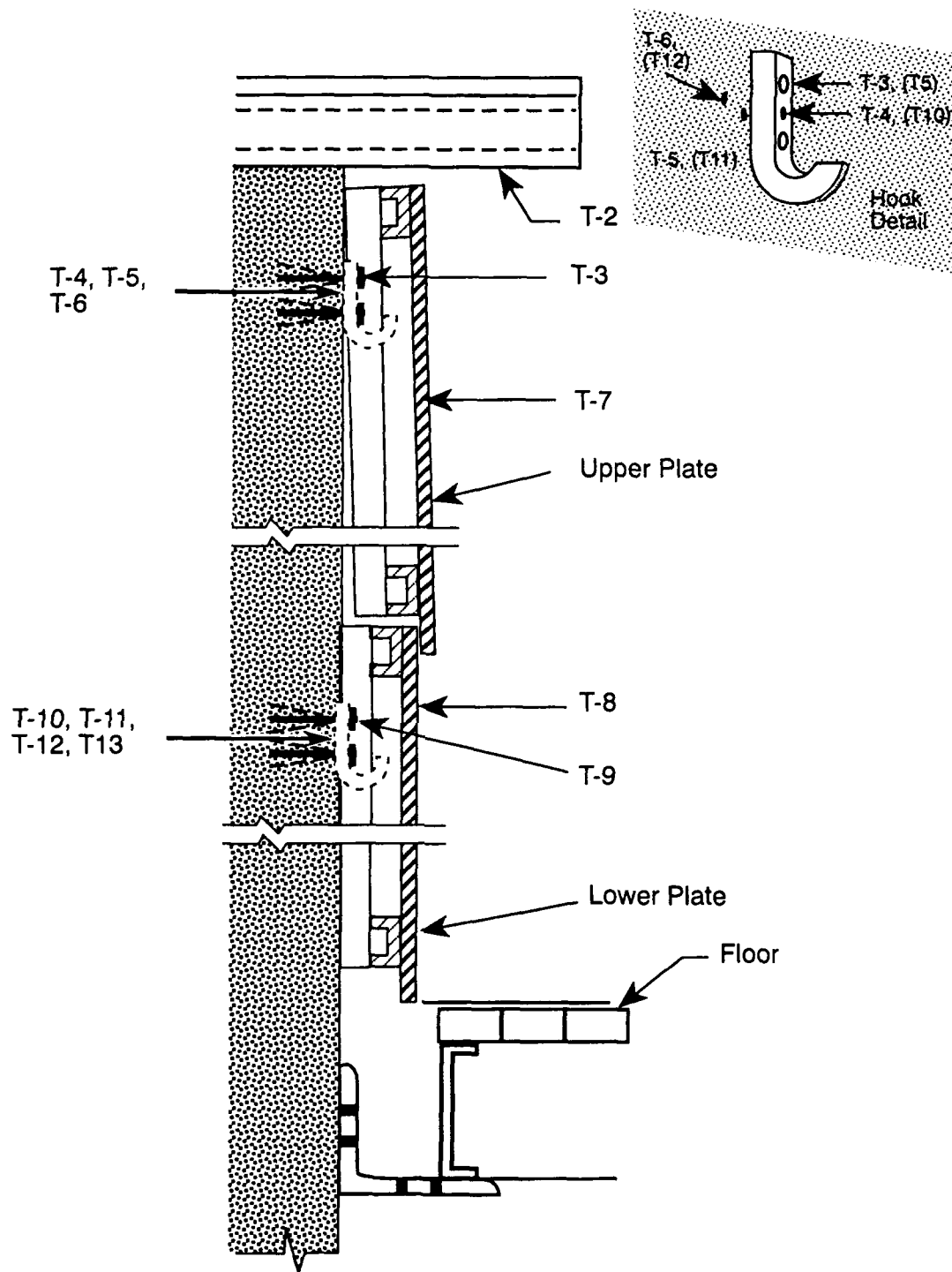


Figure 4  
 Thermocouple locations. The steel plates are supported by bent bar hooks which are anchored to the structural concrete wall.

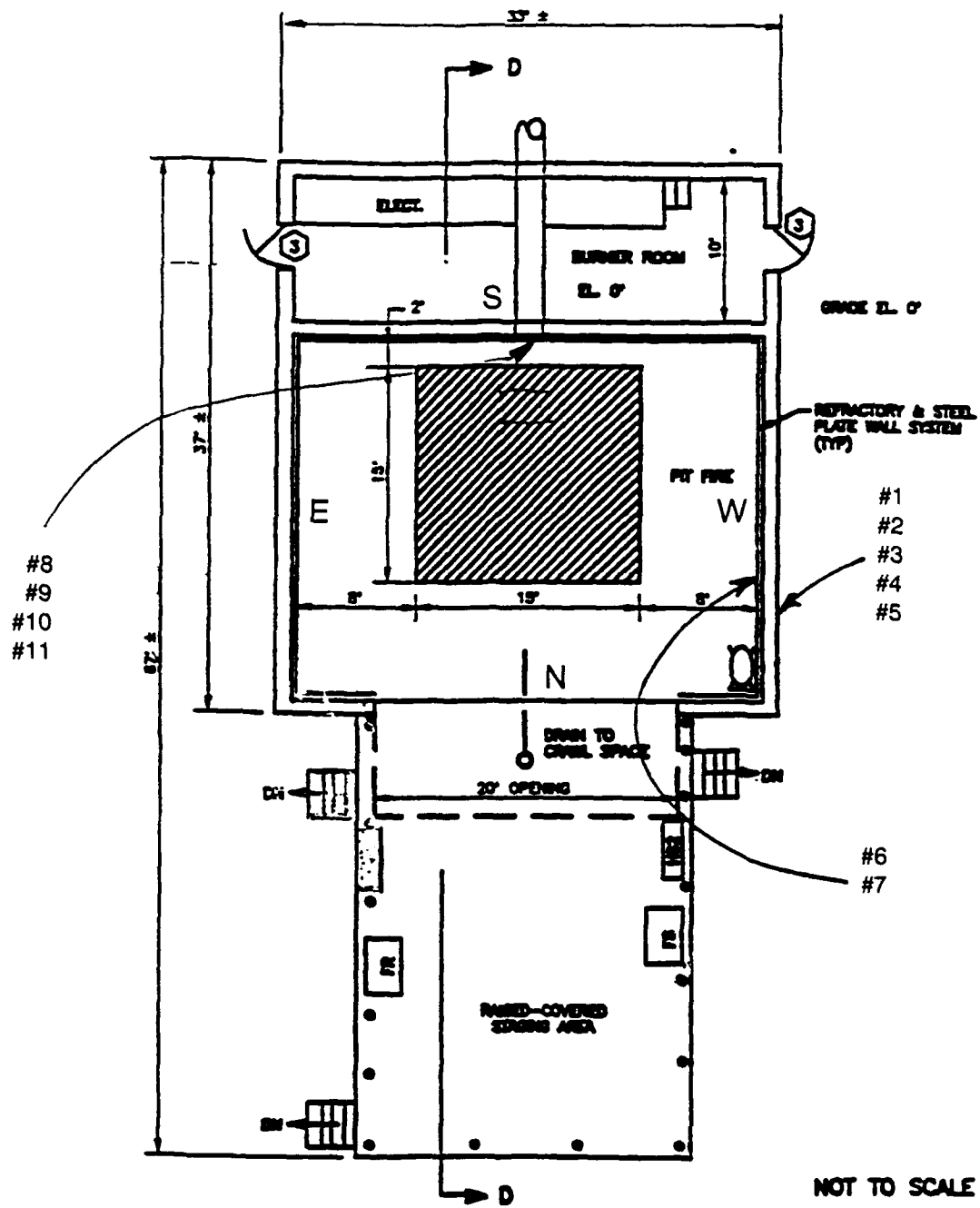


Figure 5  
Plan view of facility 19F3-B4 indicating concrete core locations.

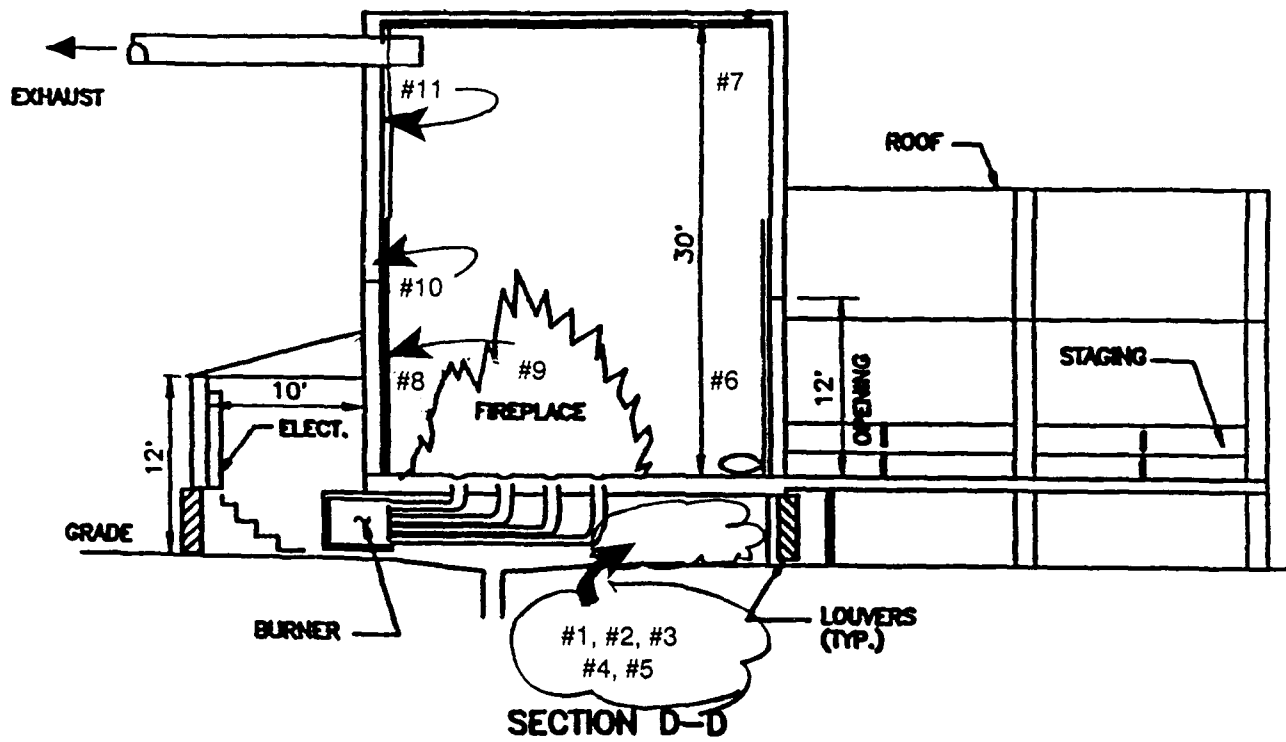


Figure 6  
Elevation view of facility 19F3-B4 indicating concrete core locations.

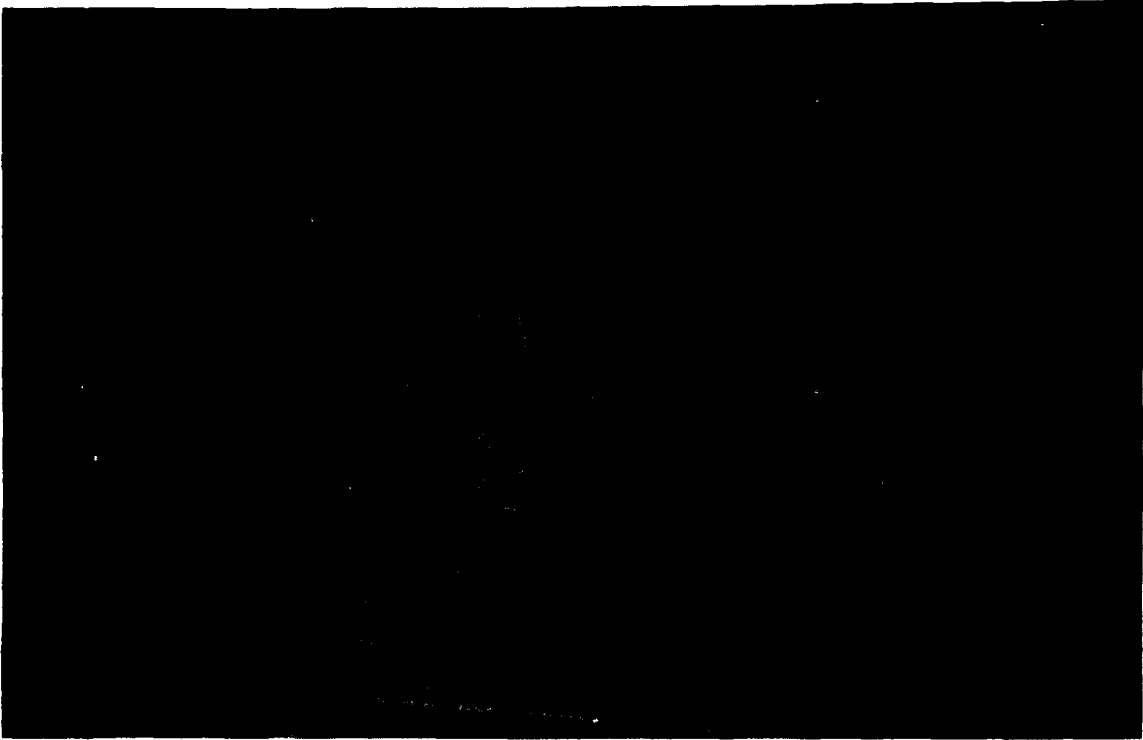


Figure 7  
Reference core samples removed from the west wall of facility 19F3-B4.



Figure 8  
Core samples tagged and readied for shipping.





Figure 9  
Plugging core openings with a nonshrinking expansive grout.

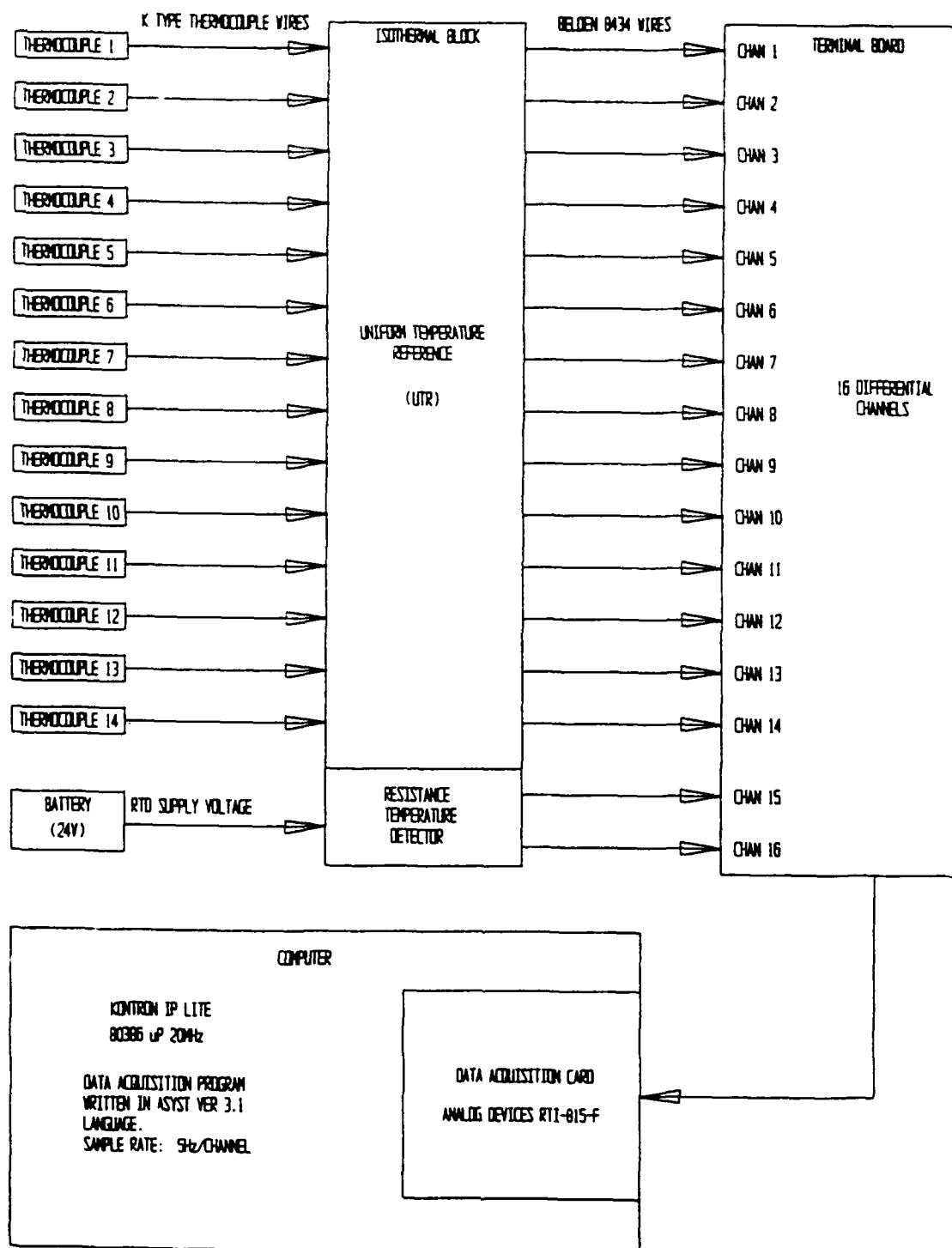


Figure 10  
Data acquisition system block diagram.

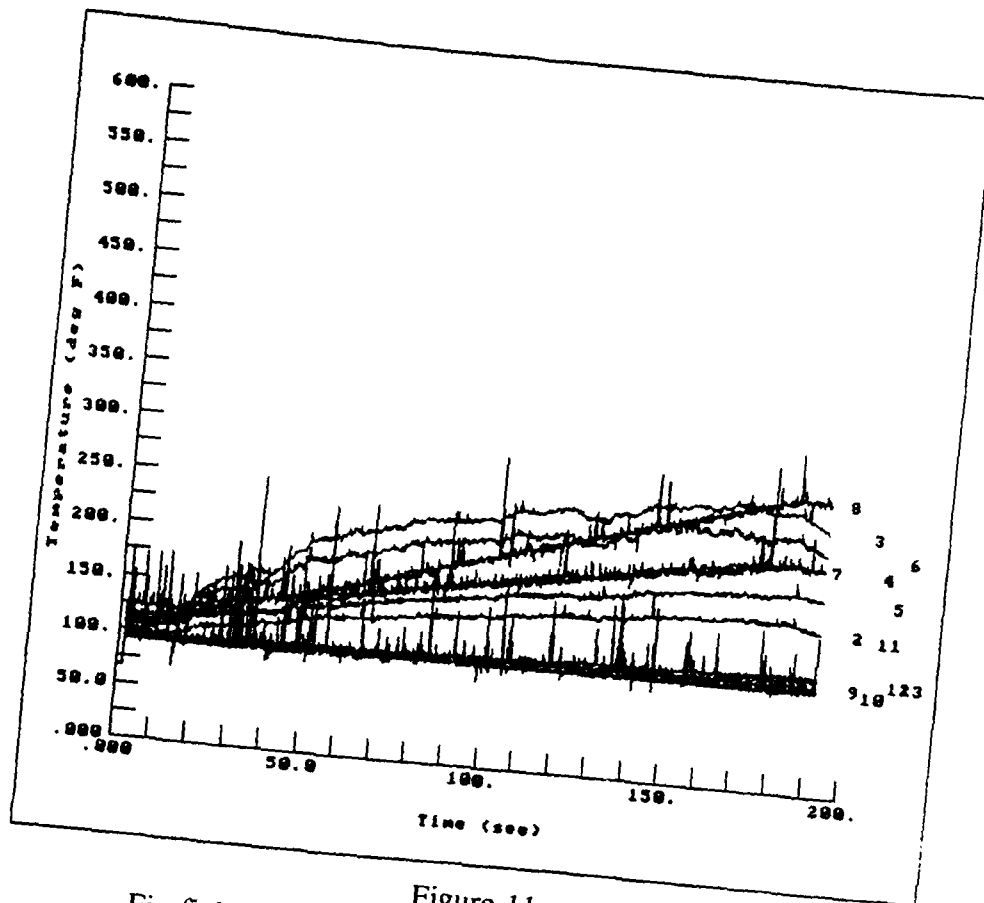


Figure 11  
Firefighting trainer temperature cycling test - Run 1.

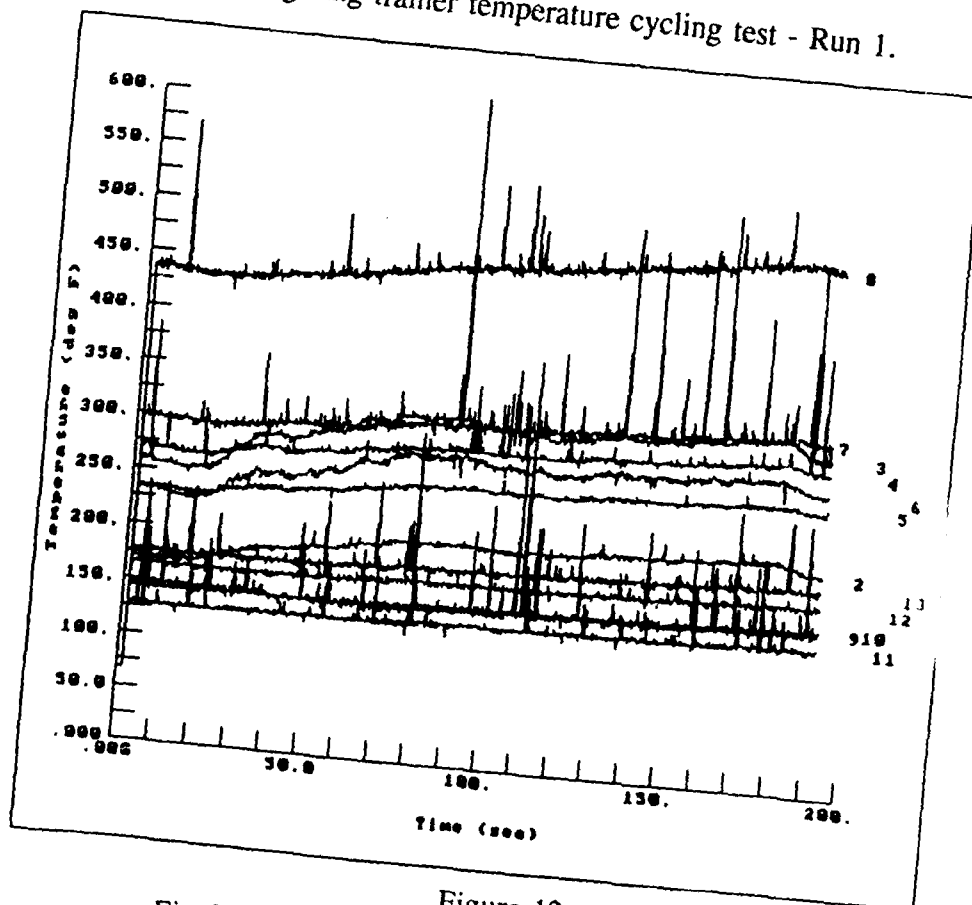


Figure 12  
Firefighting trainer temperature cycling test - Run 5.

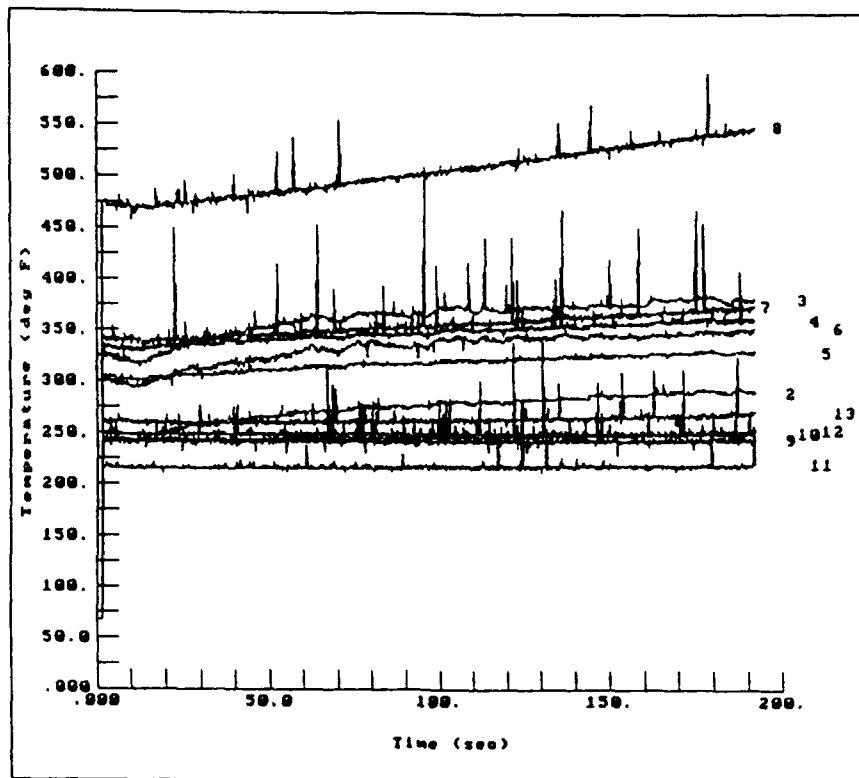


Figure 13  
Firefighting trainer temperature cycling test - Run 15.

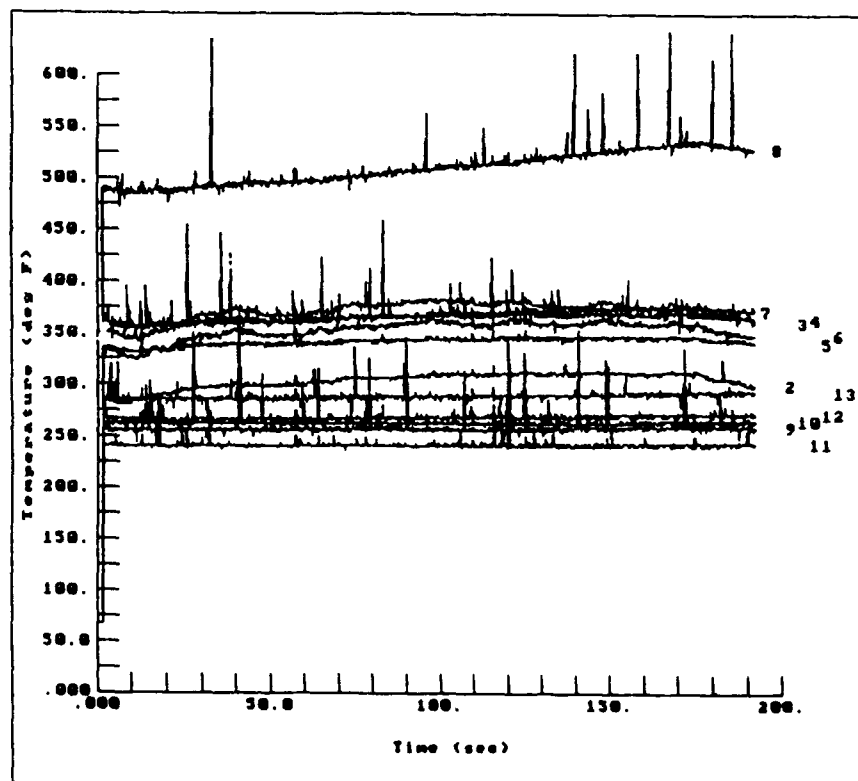


Figure 14  
Firefighting trainer temperature cycling test - Run 28.

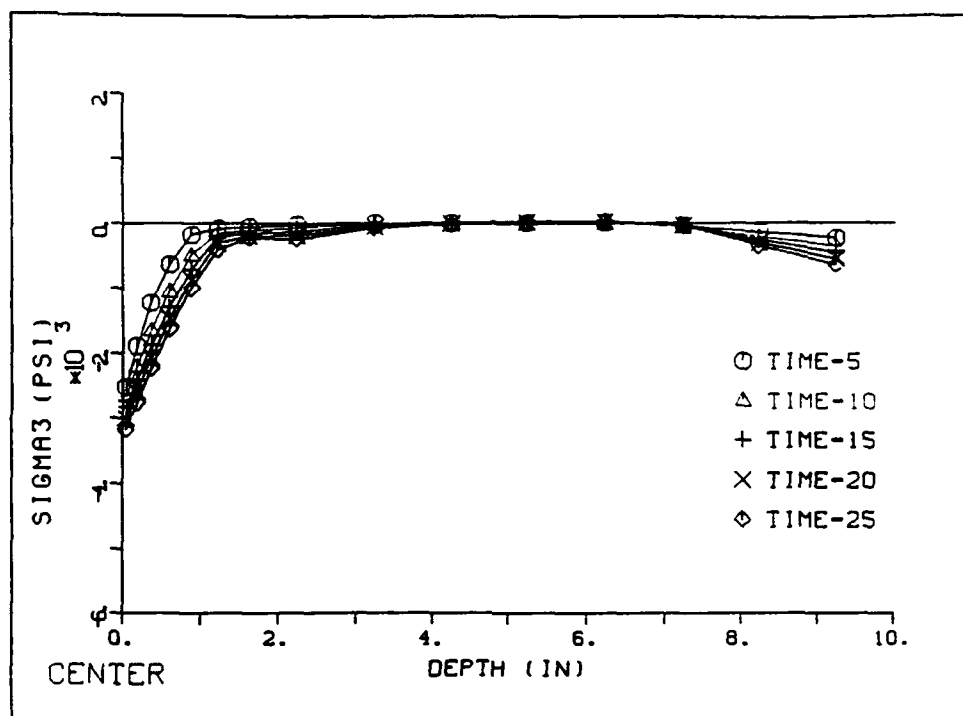


Figure 15  
Temperature-induced third principal stress,  $\sigma_3$  - uniform wall.

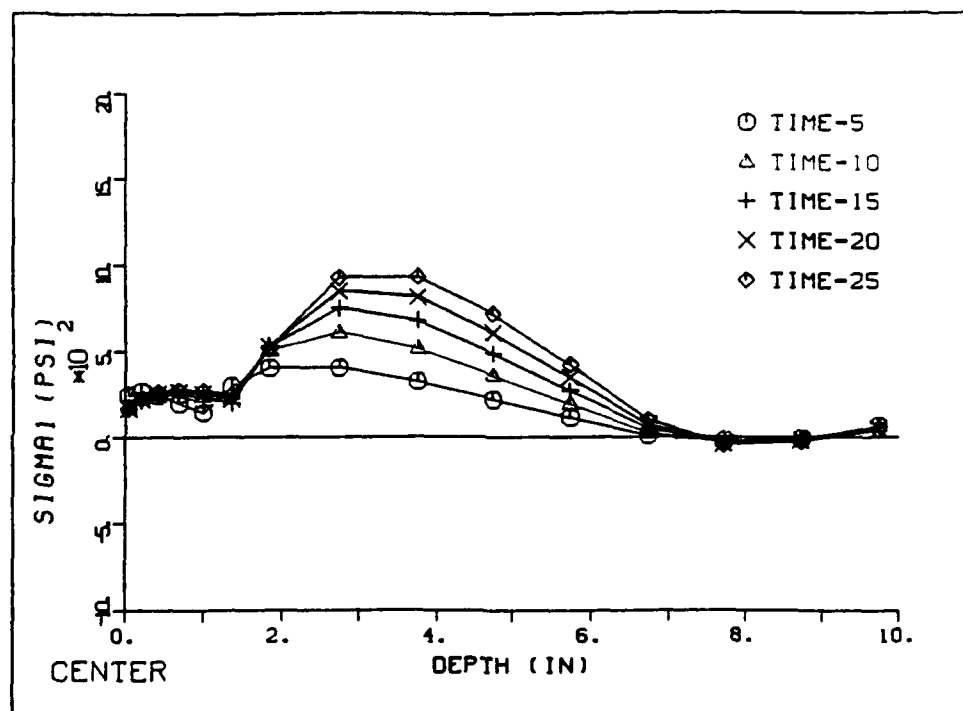


Figure 16  
Temperature-induced first principal stress,  $\sigma_1$  - uniform wall.

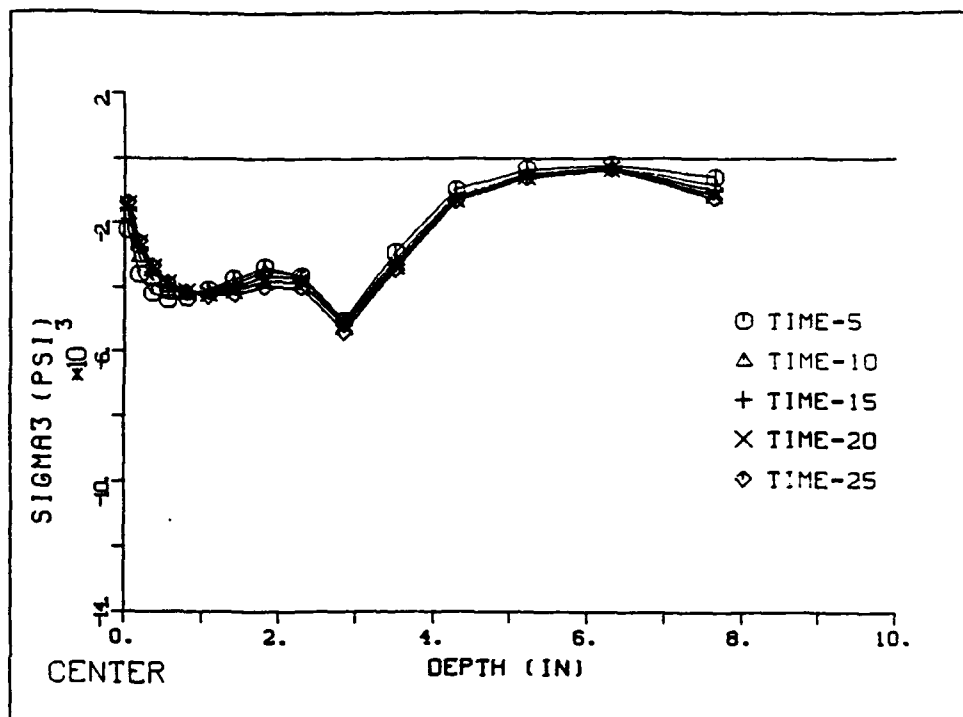


Figure 17  
Temperature-induced third principal stress,  $\sigma_3$  - wall with embedded bolt.

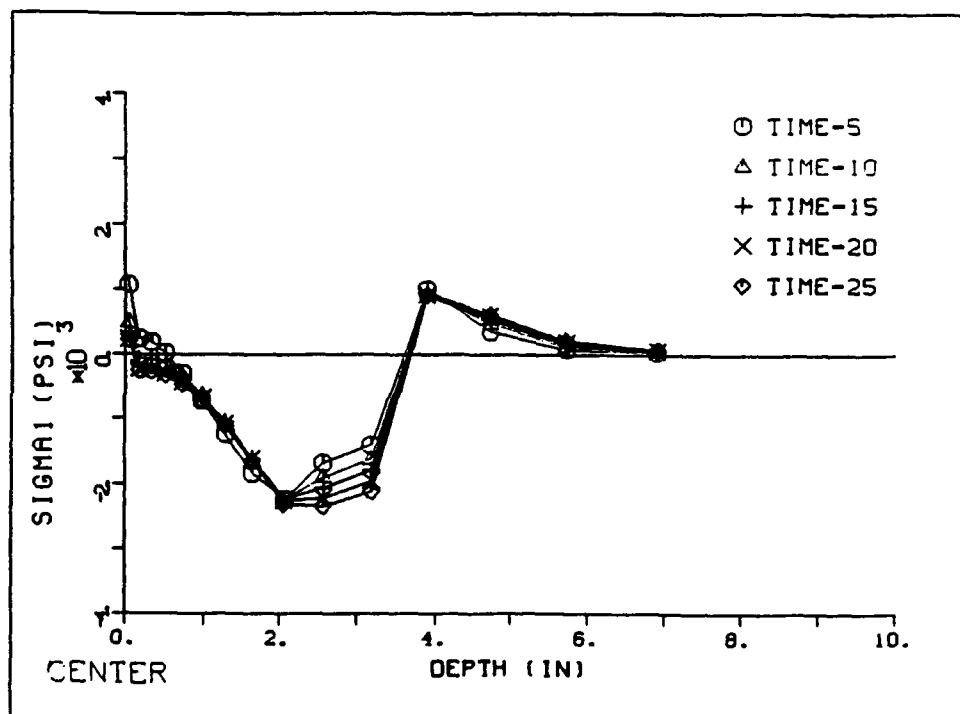
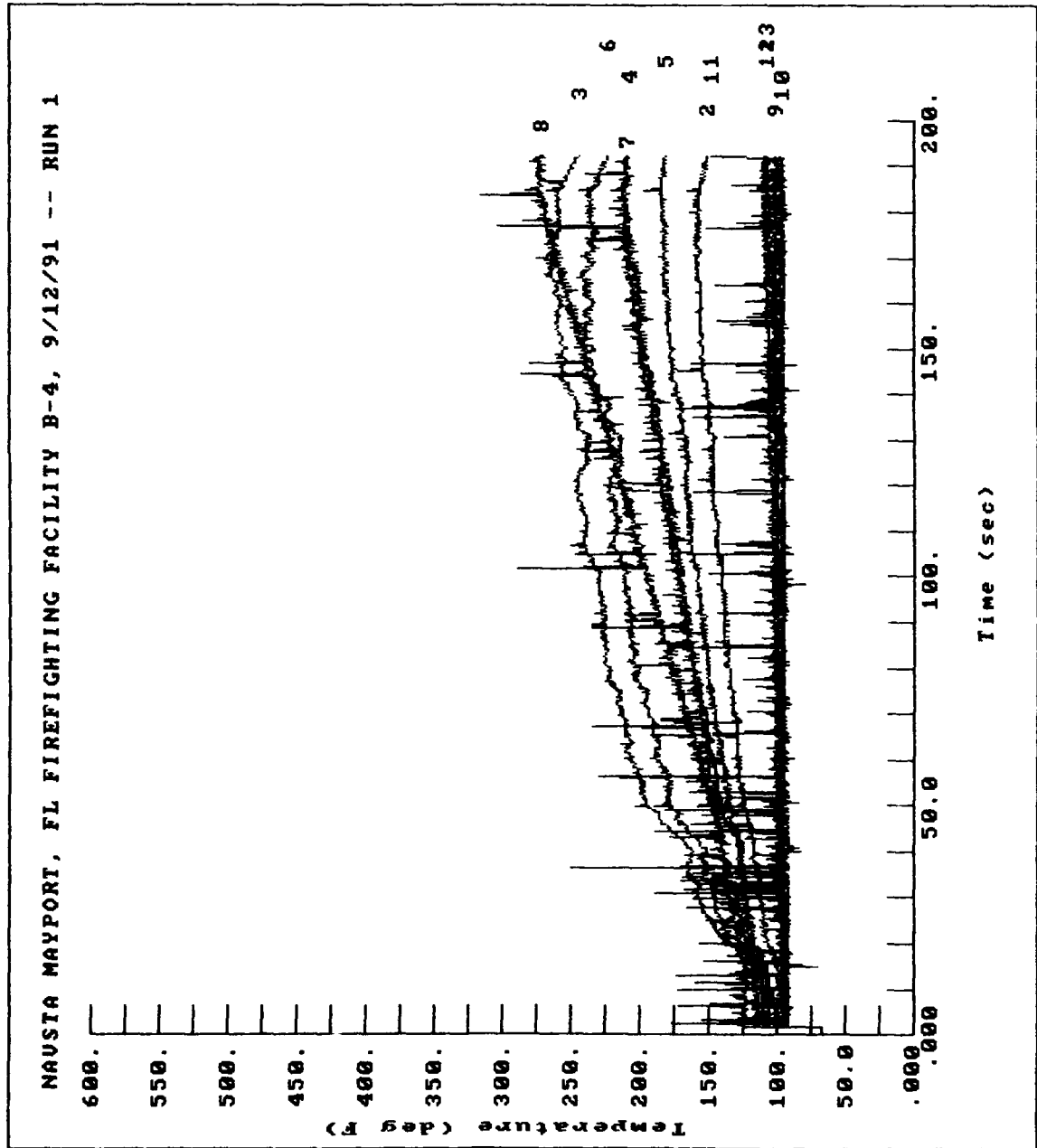


Figure 18  
Temperature-induced first principal stress  $\sigma_1$  - wall with embedded bolt.

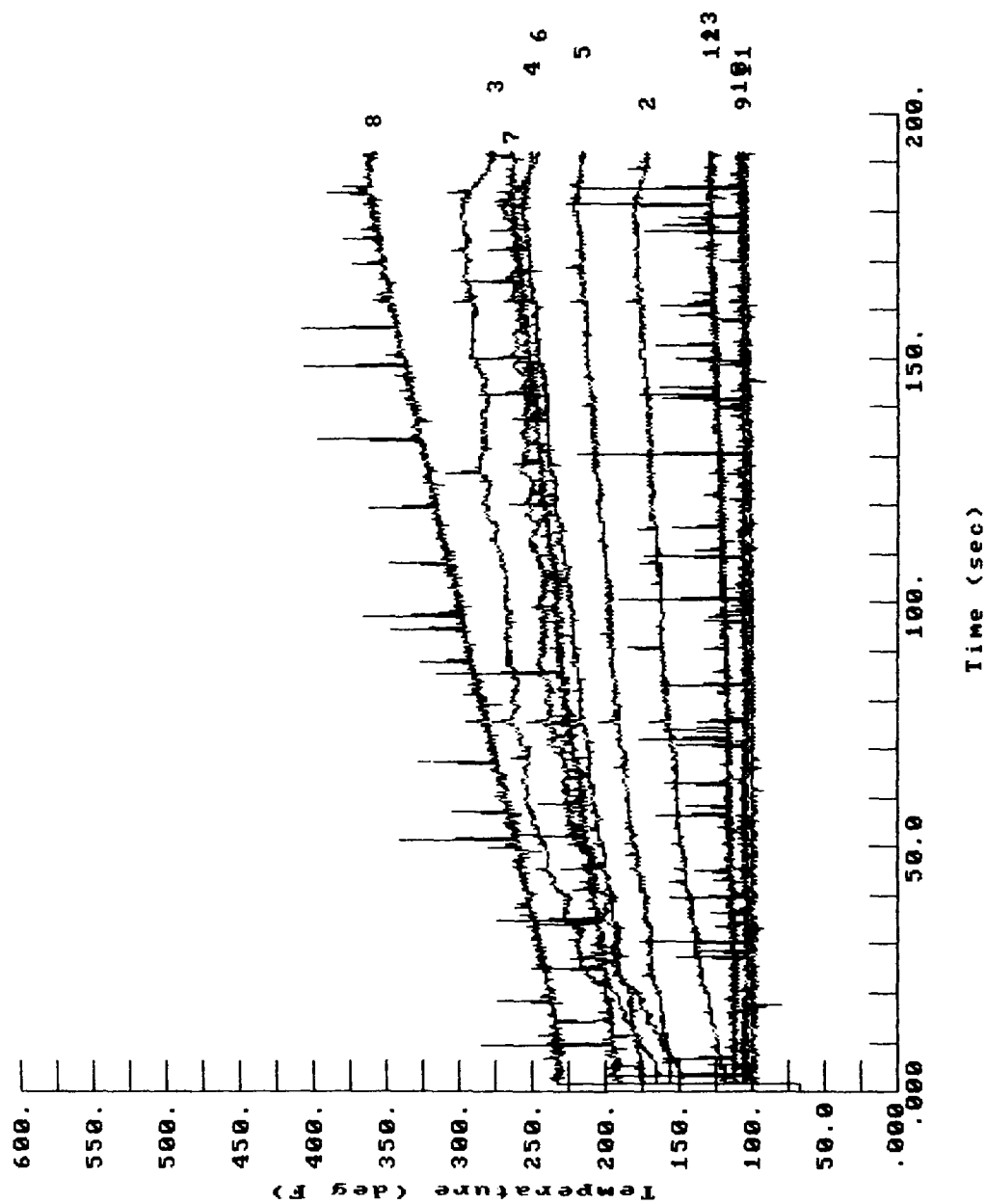
**Appendix A**

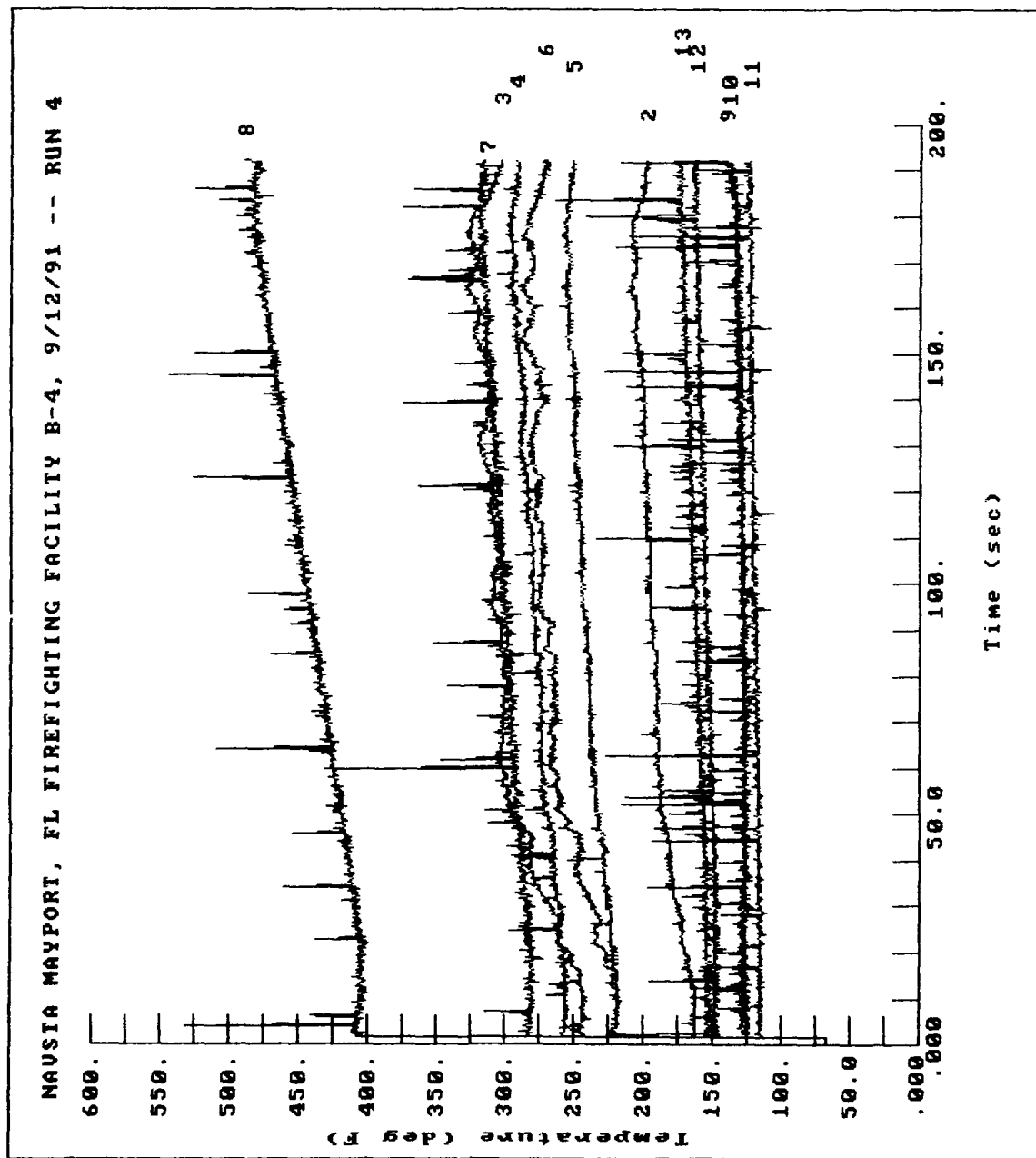
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TRAINER TEMPERATURE CYCLING TEST**

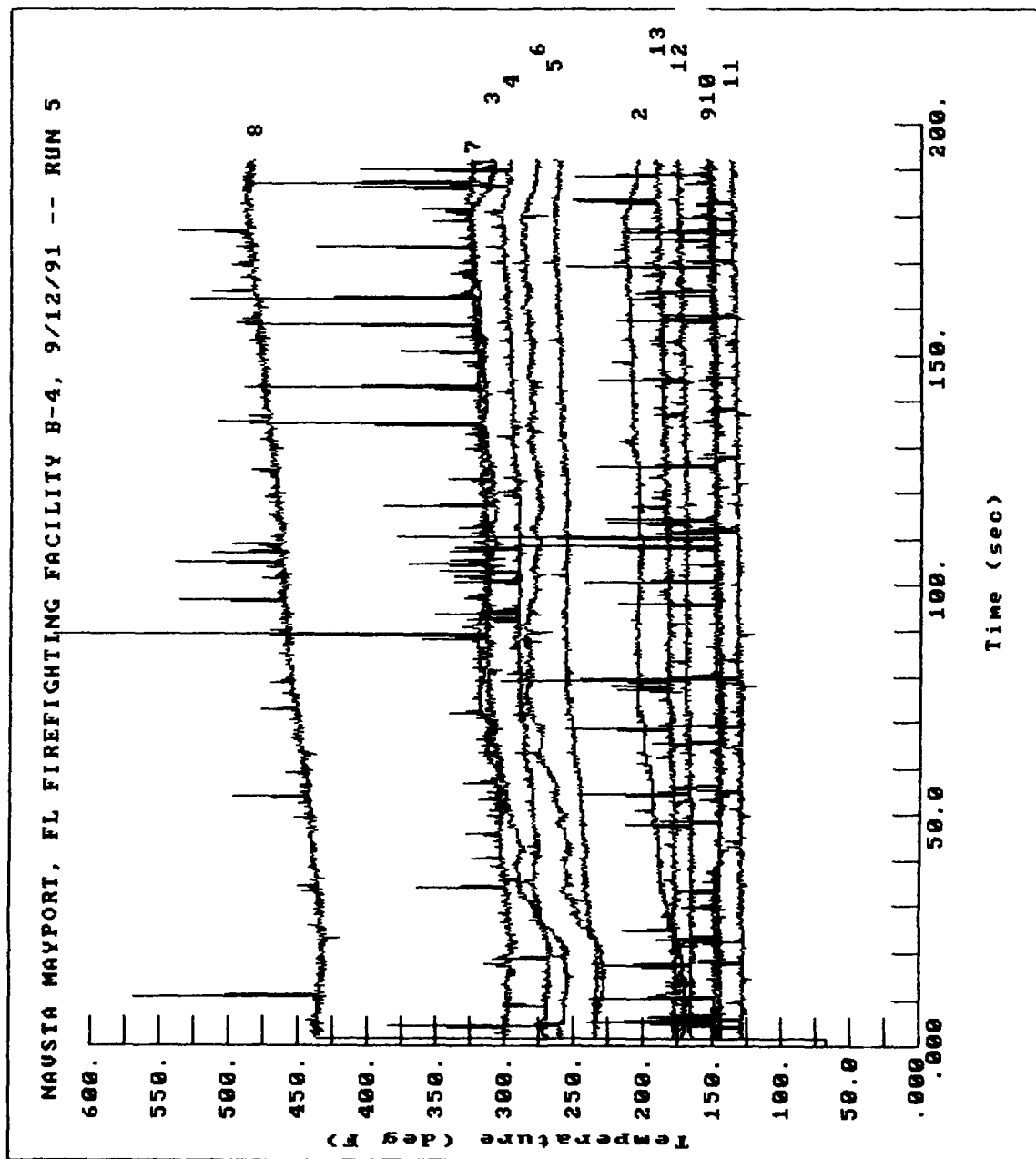


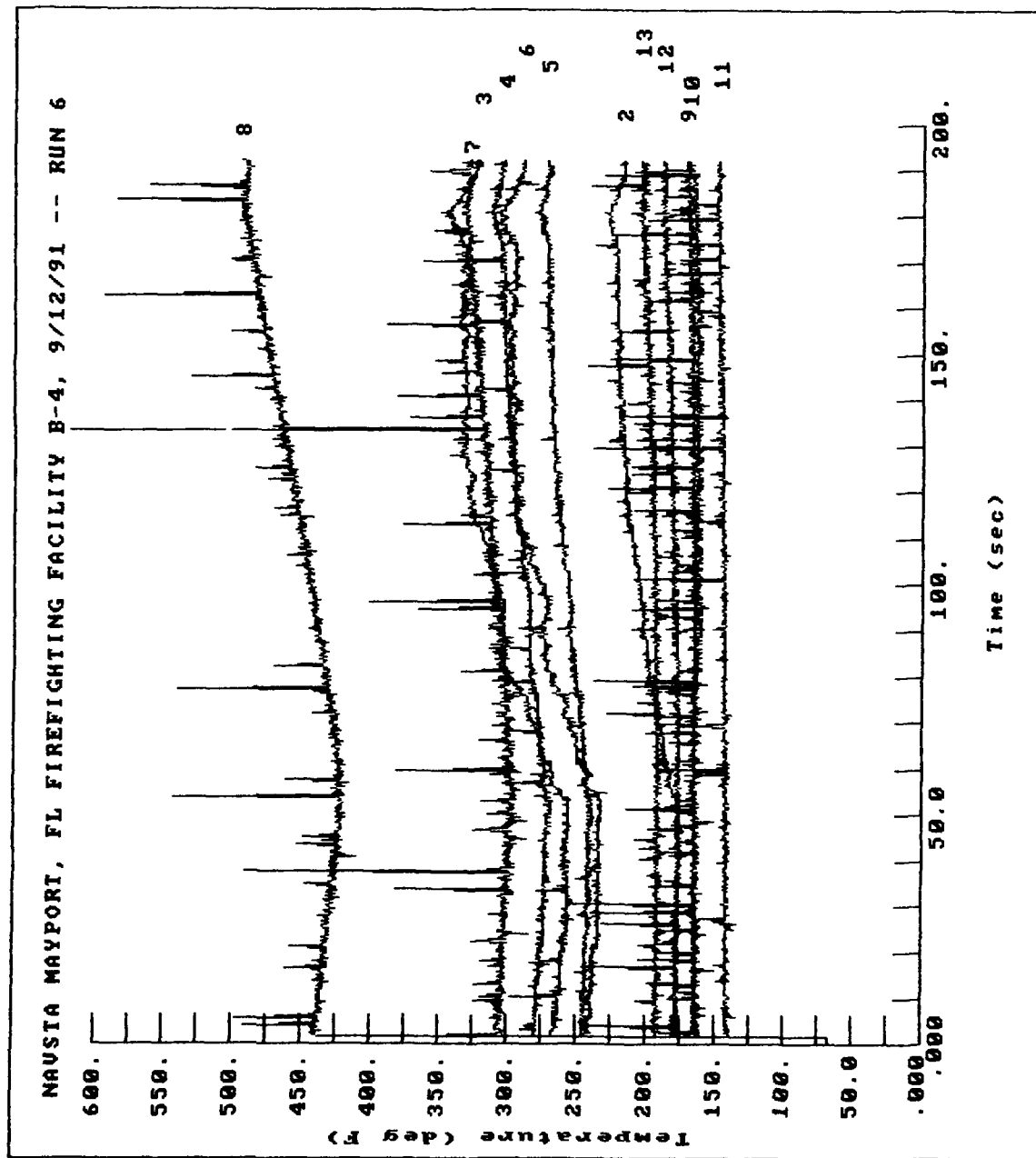


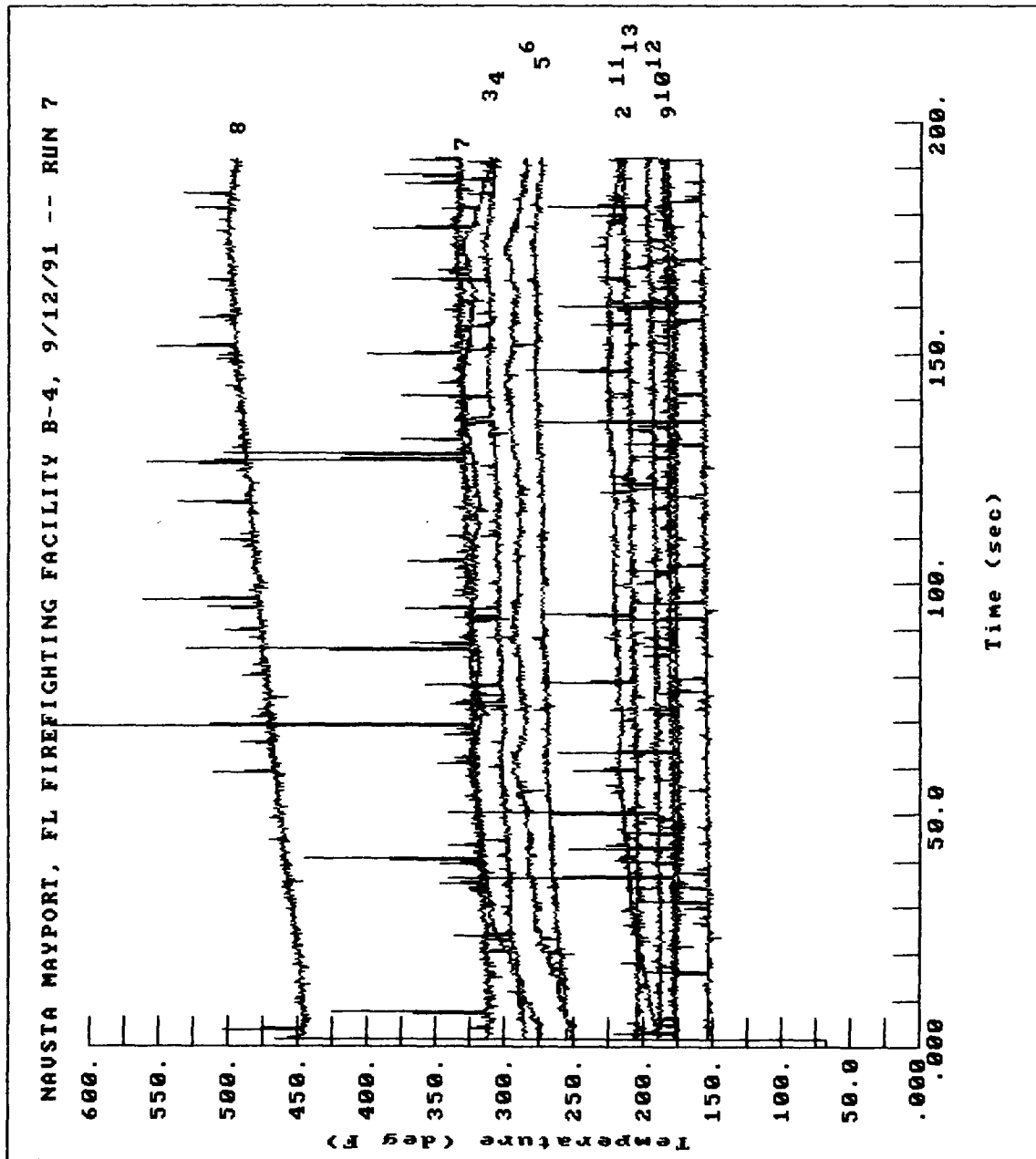
NAUSTIA MAYPORT, FL FIREFIGHTING FACILITY B-4, 9/12/91 -- RUN 2

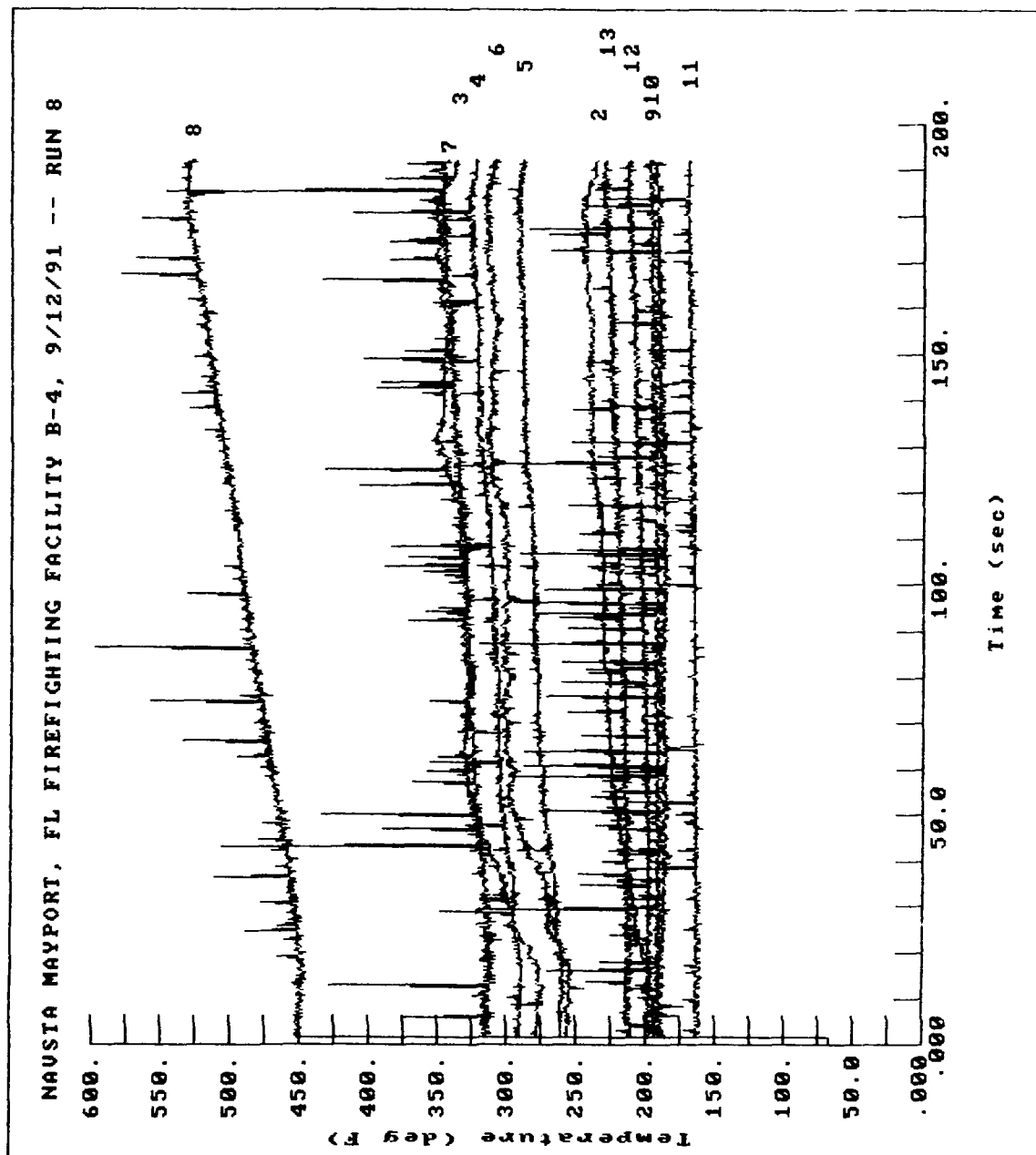


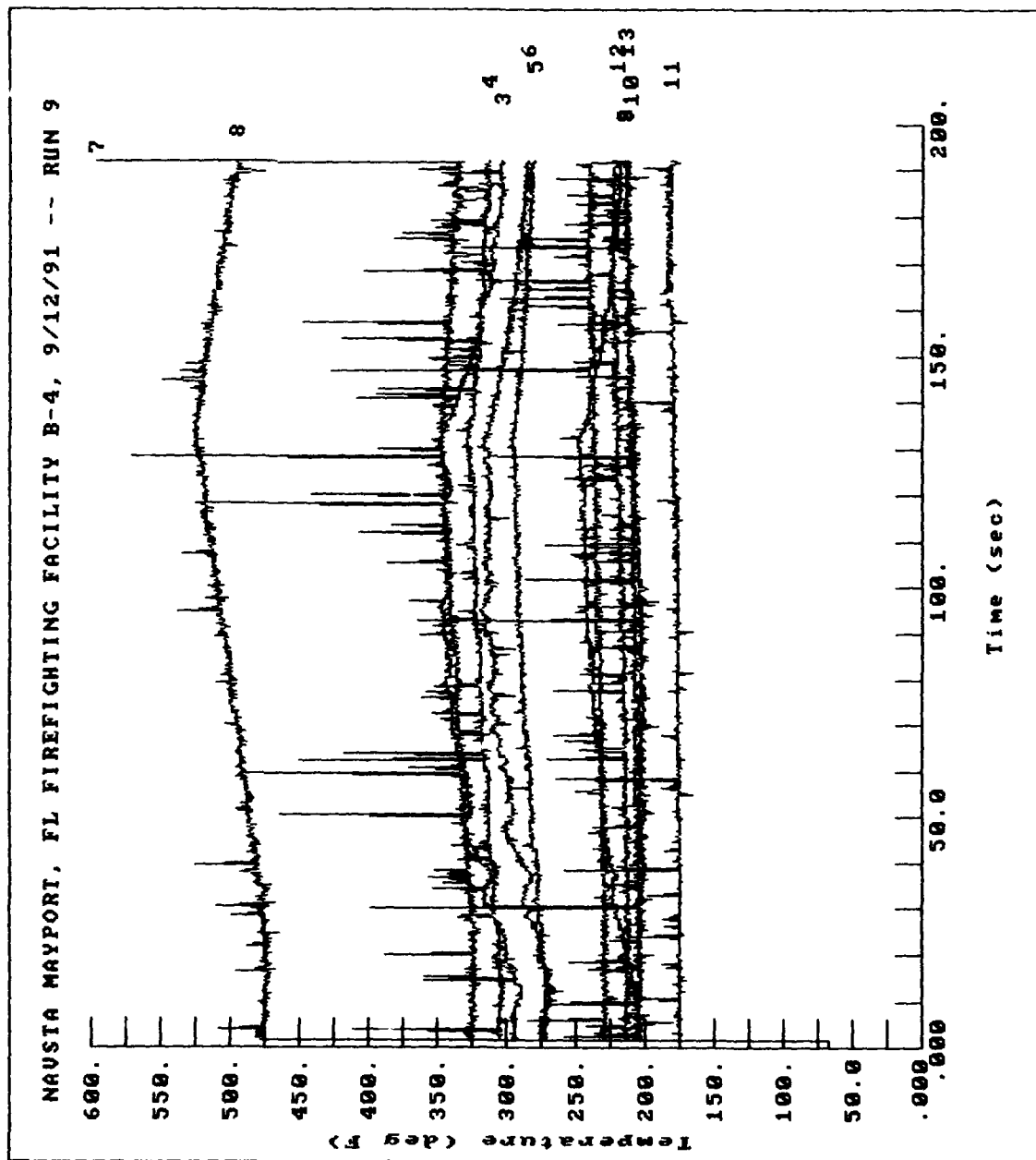


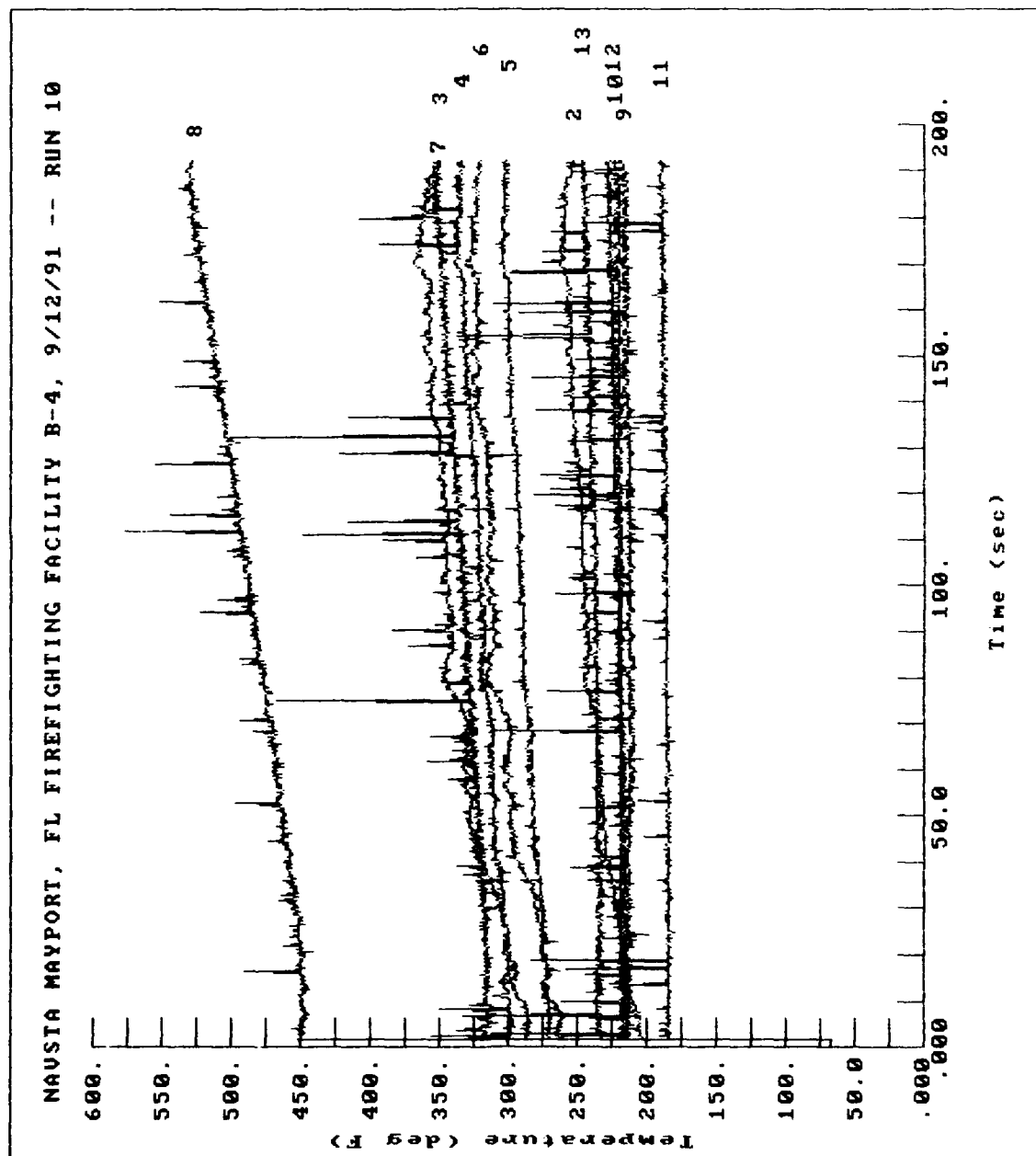




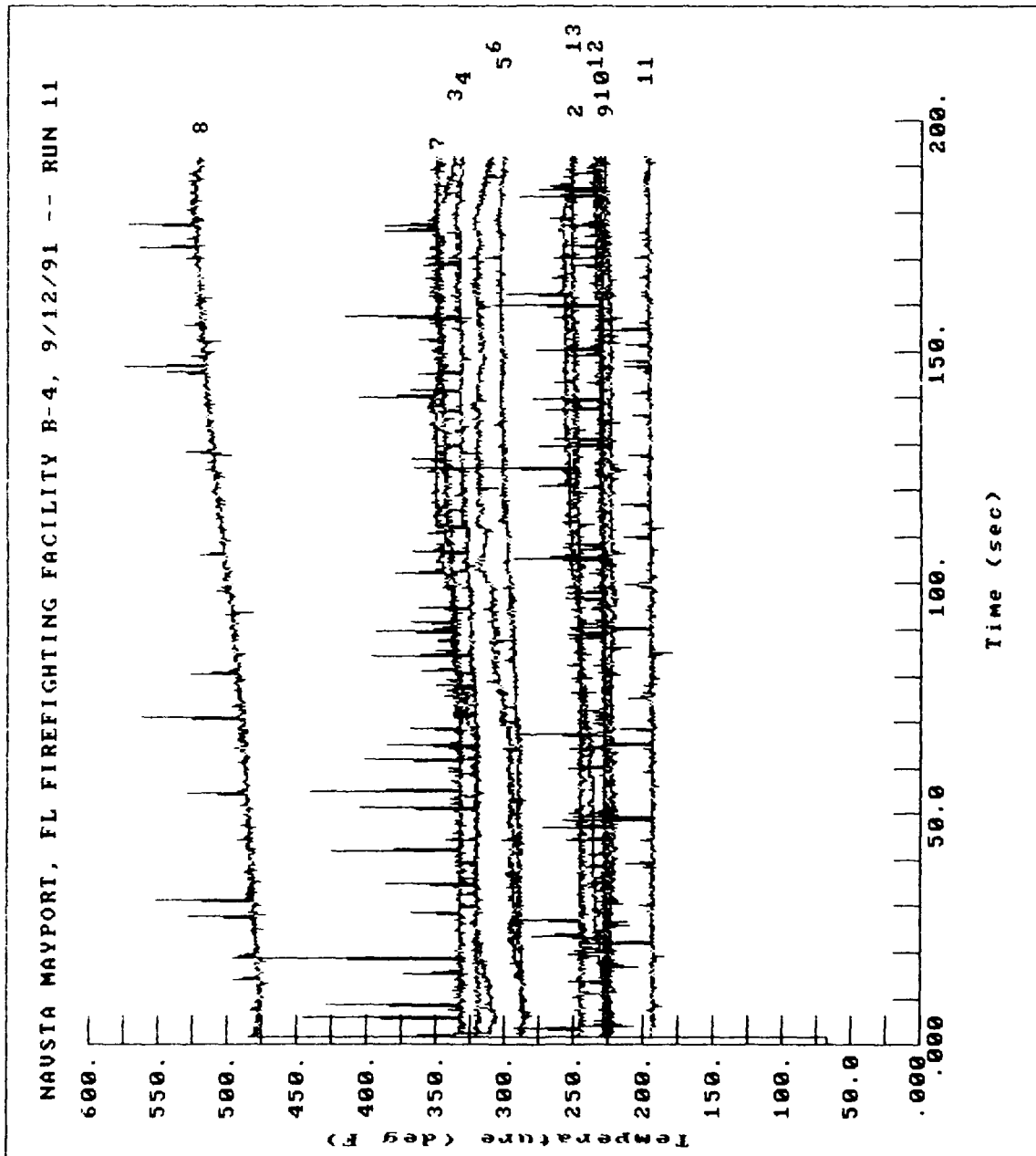


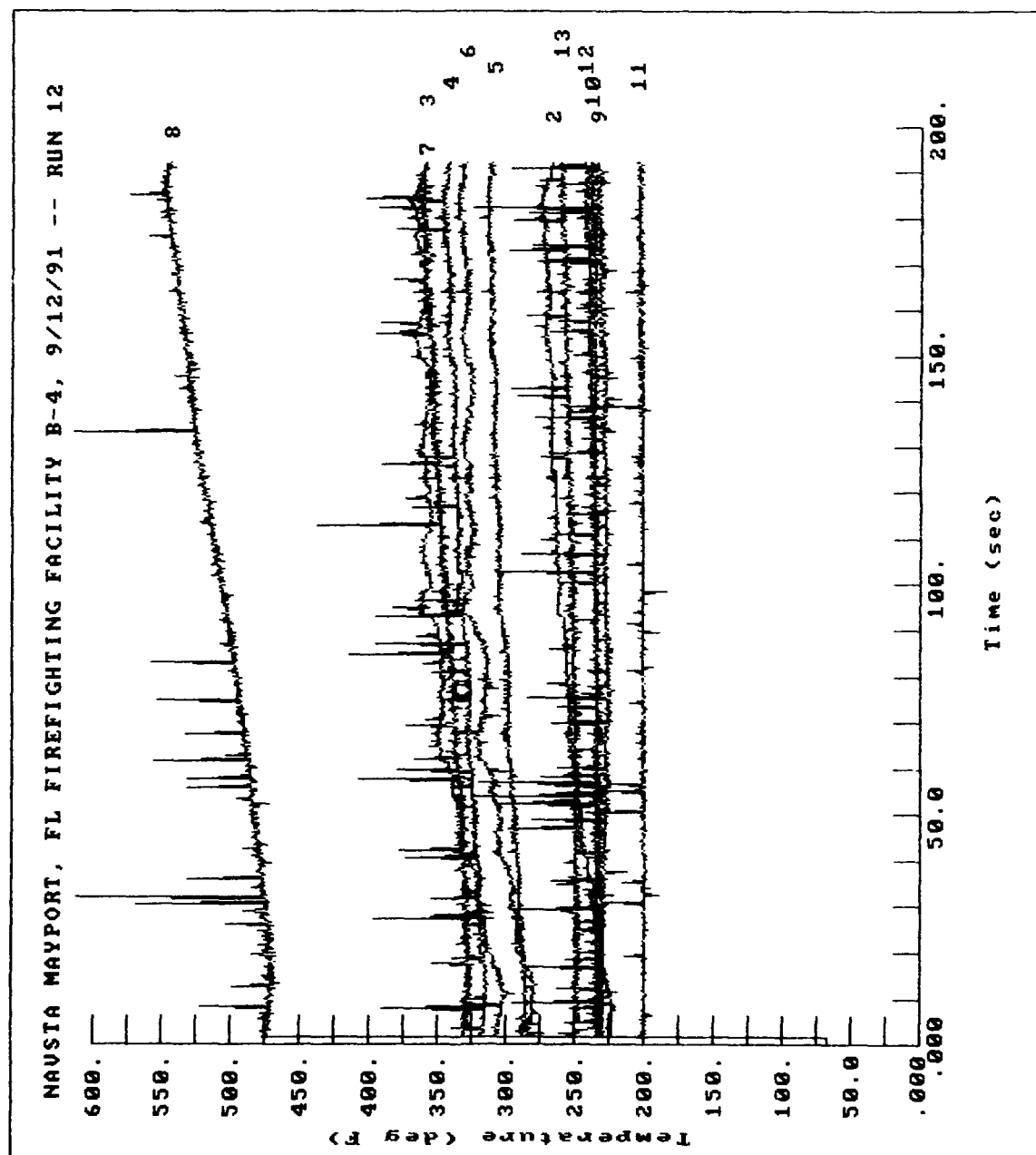


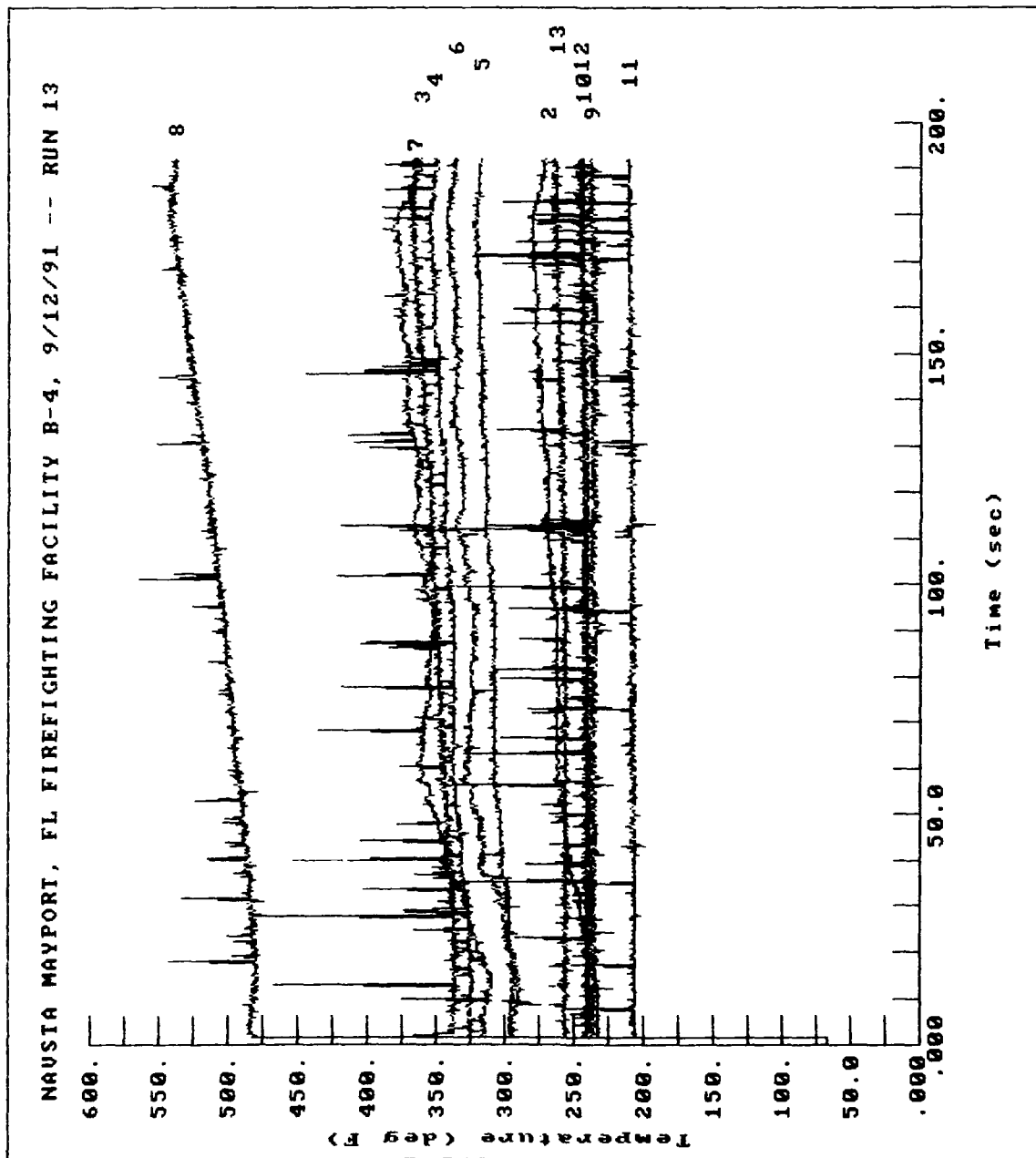


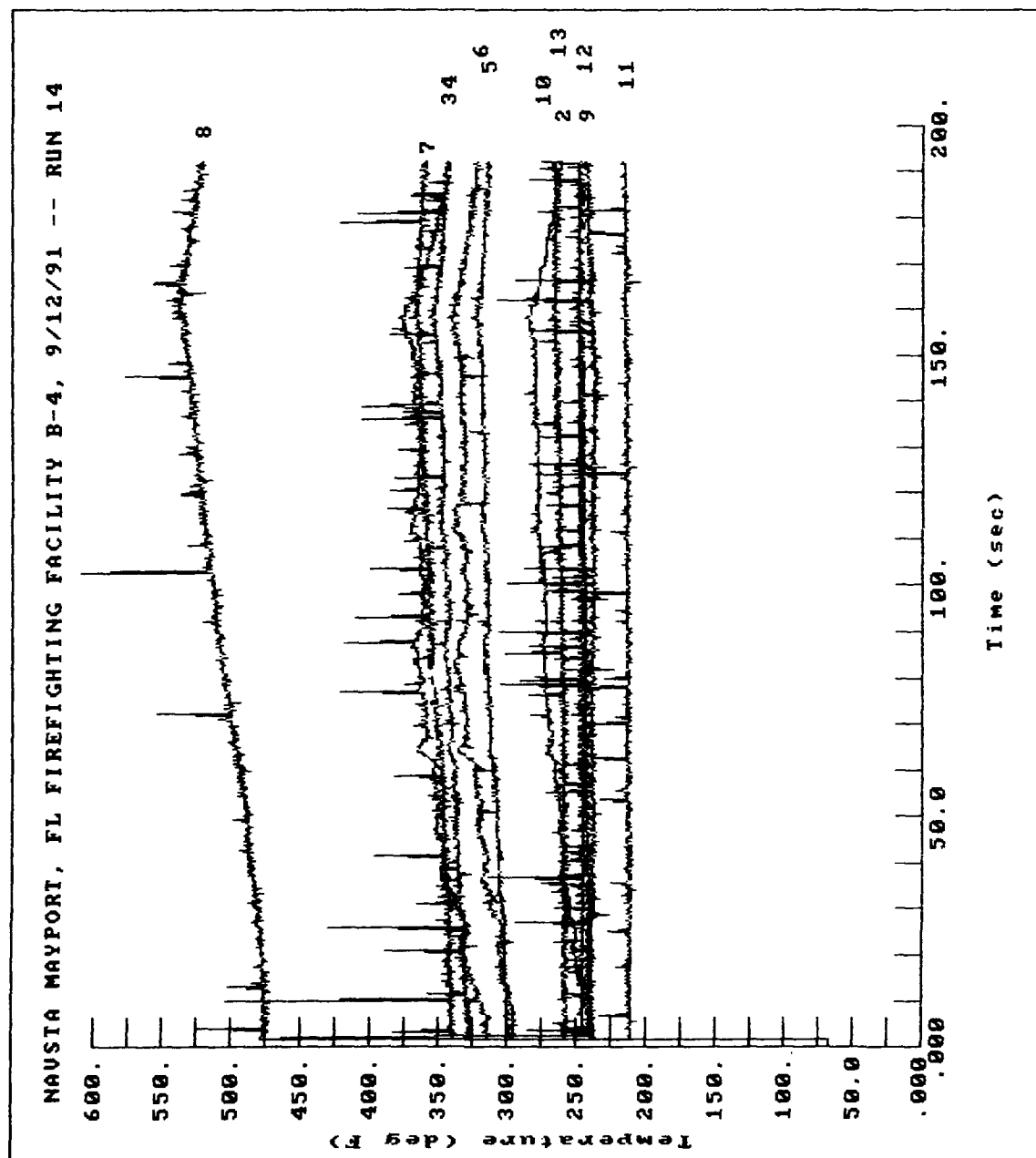


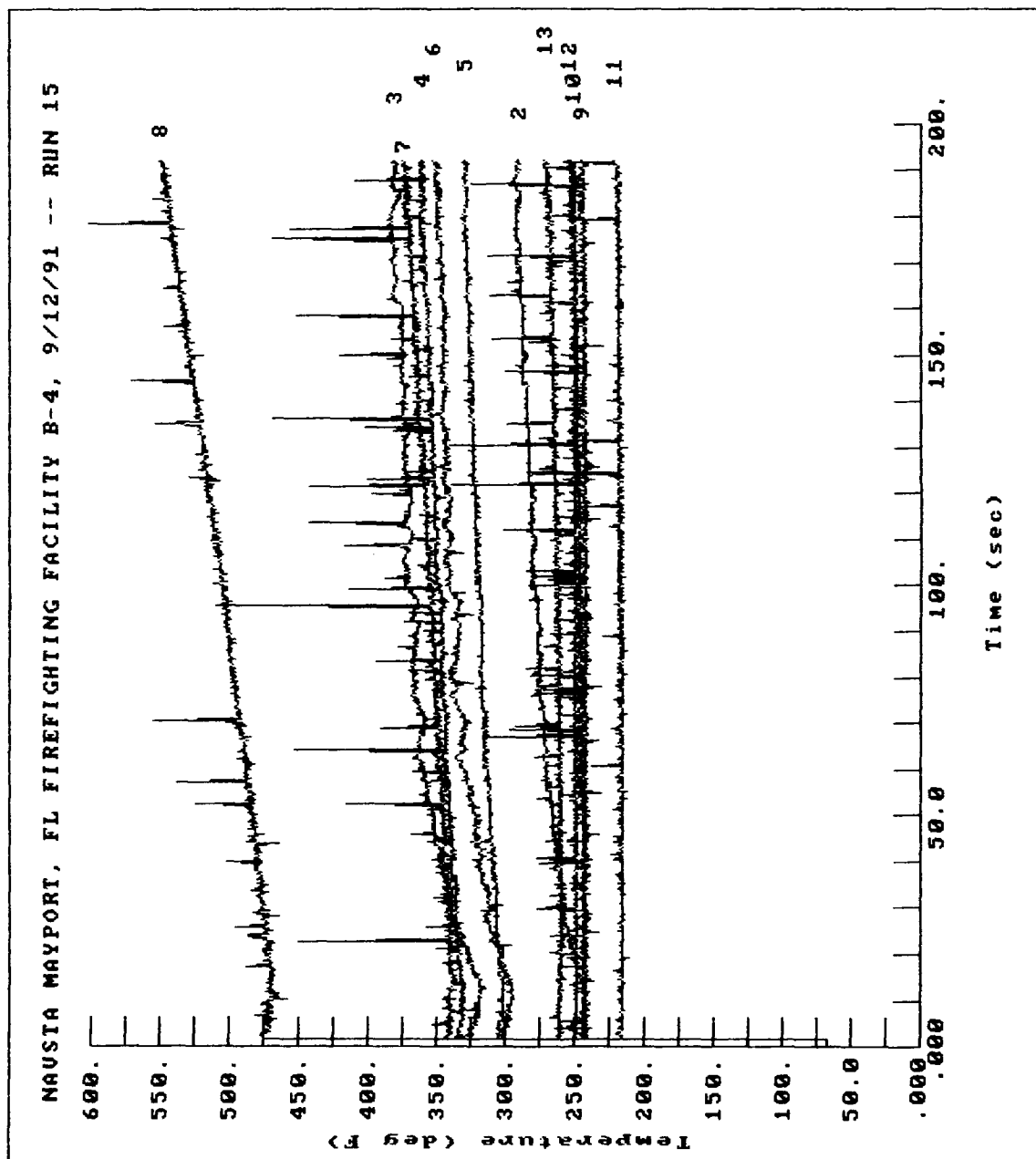


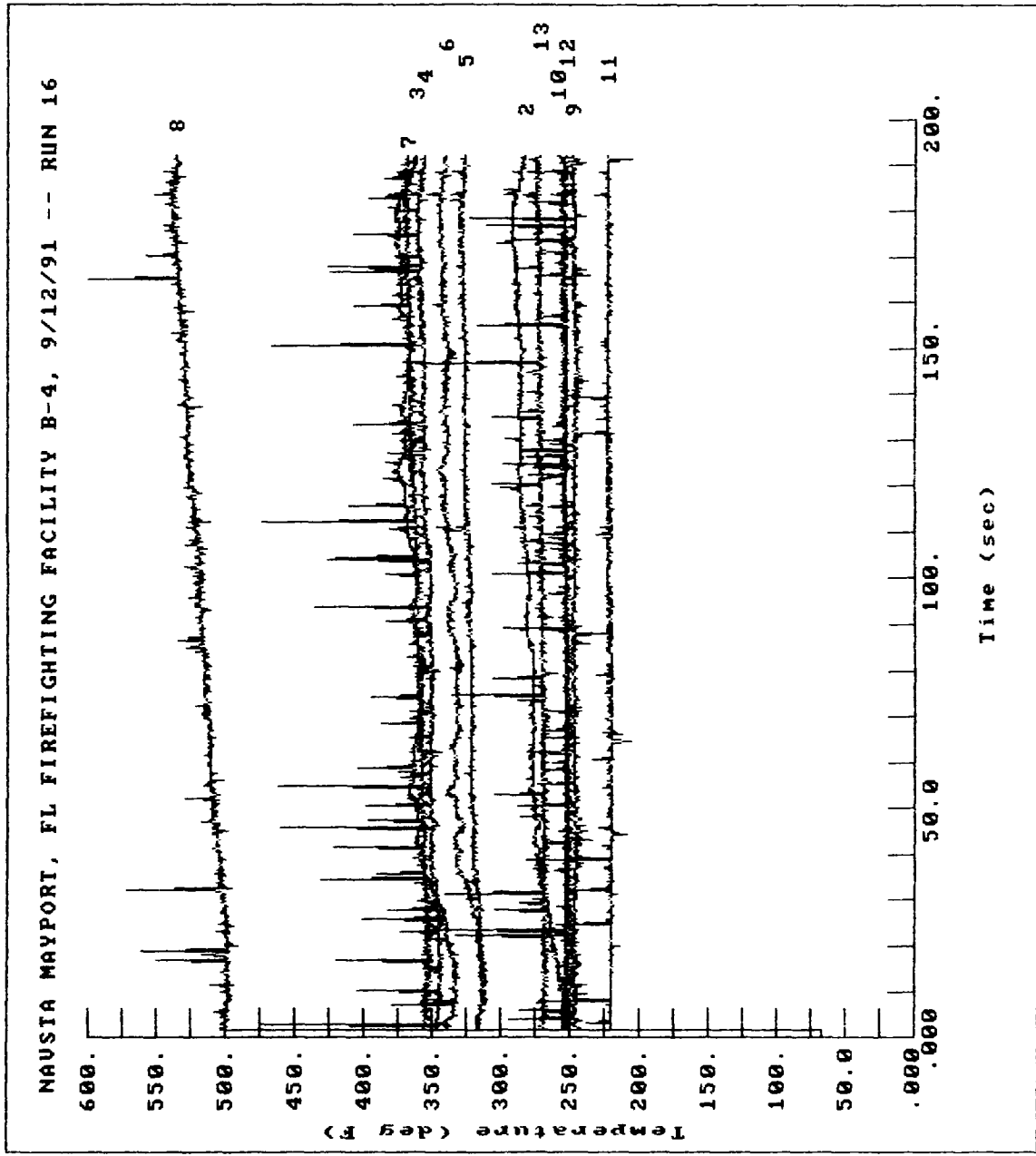


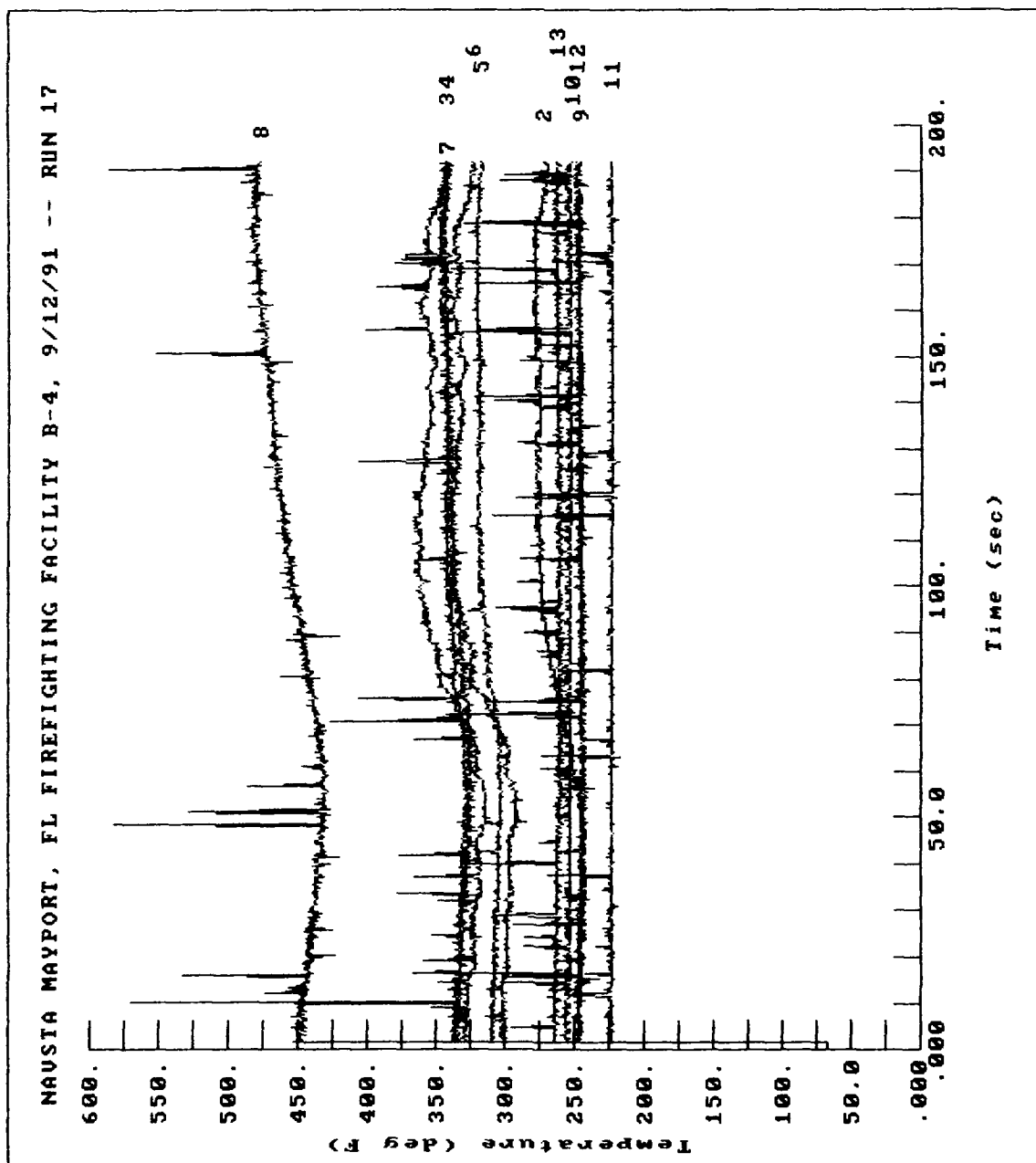


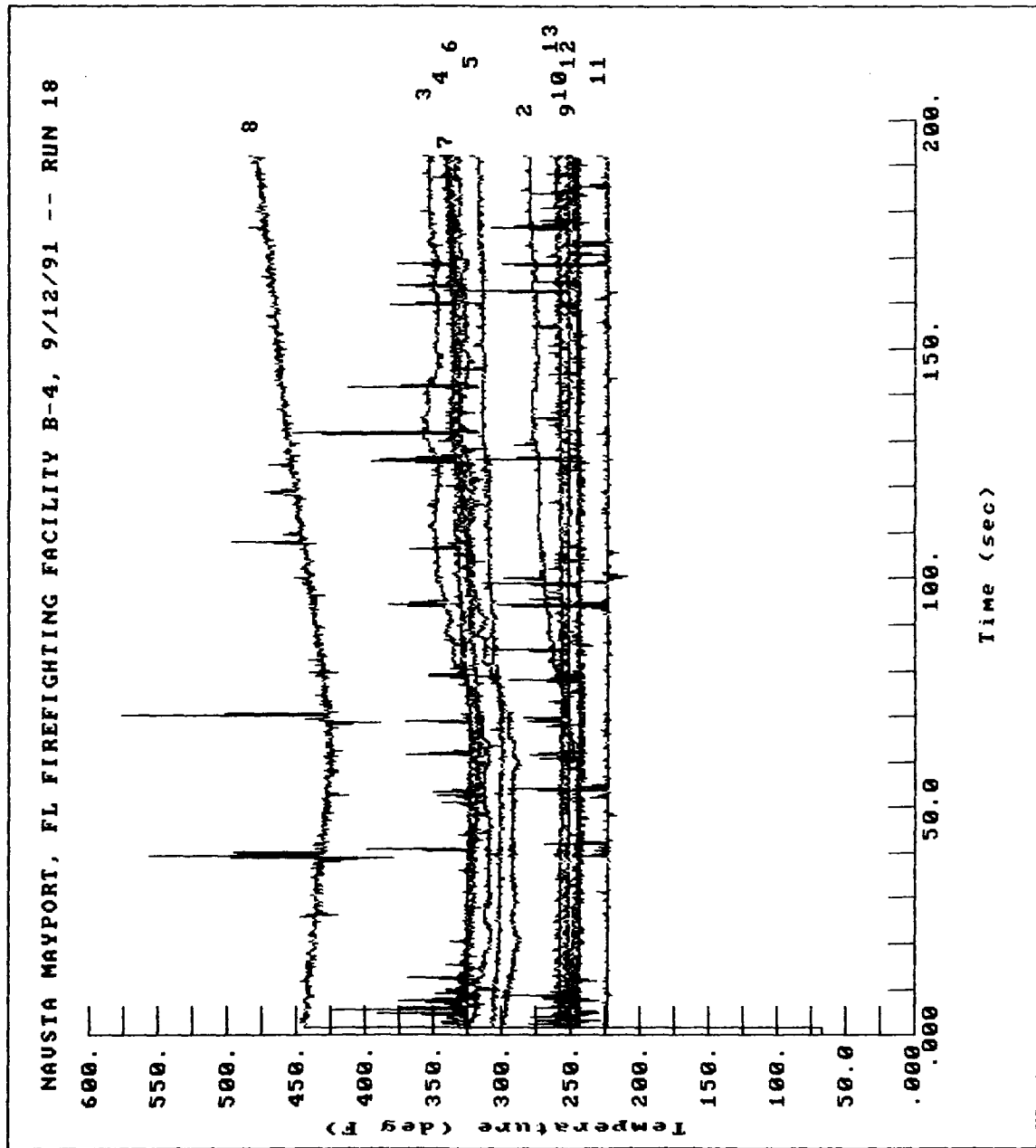




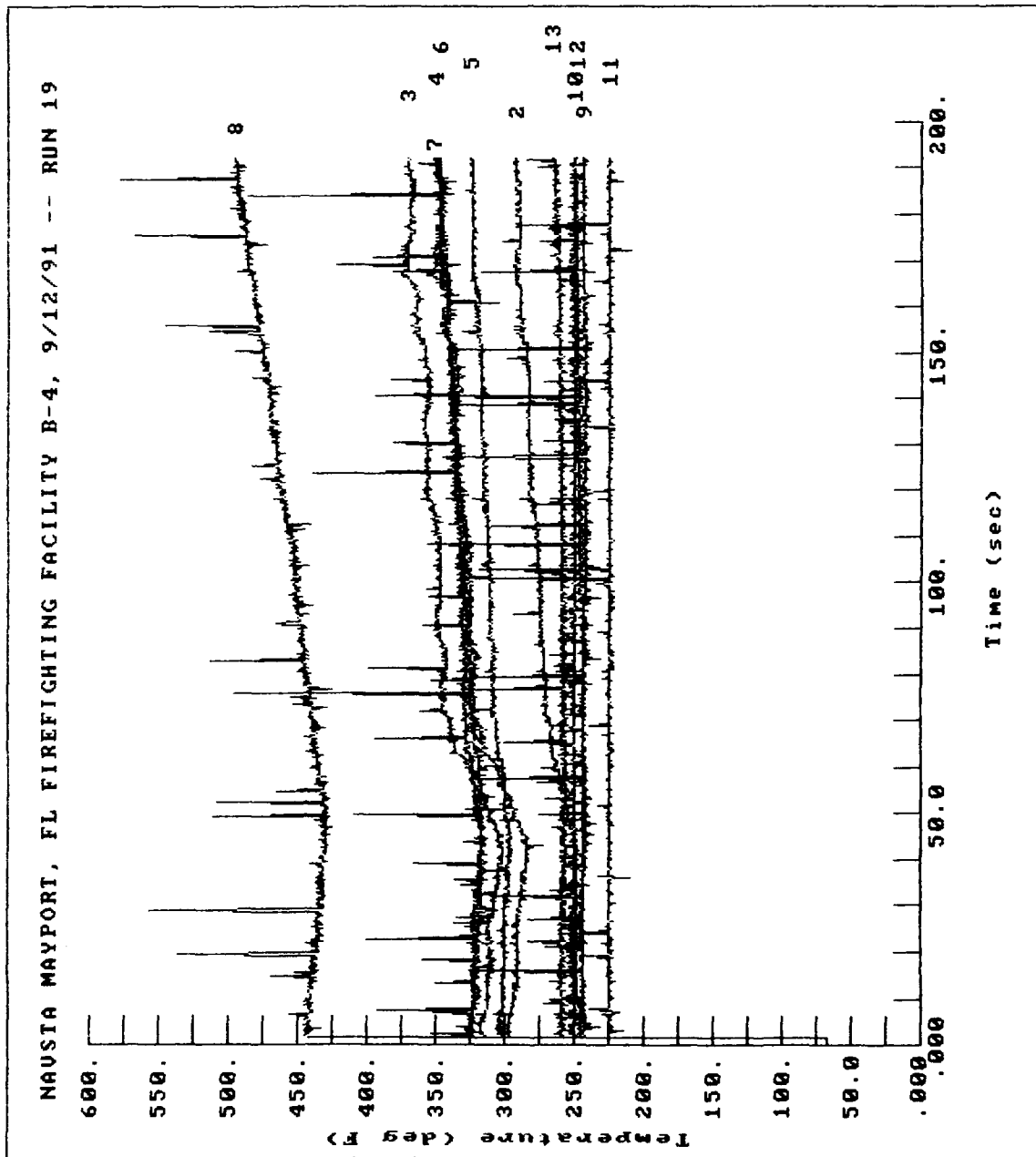


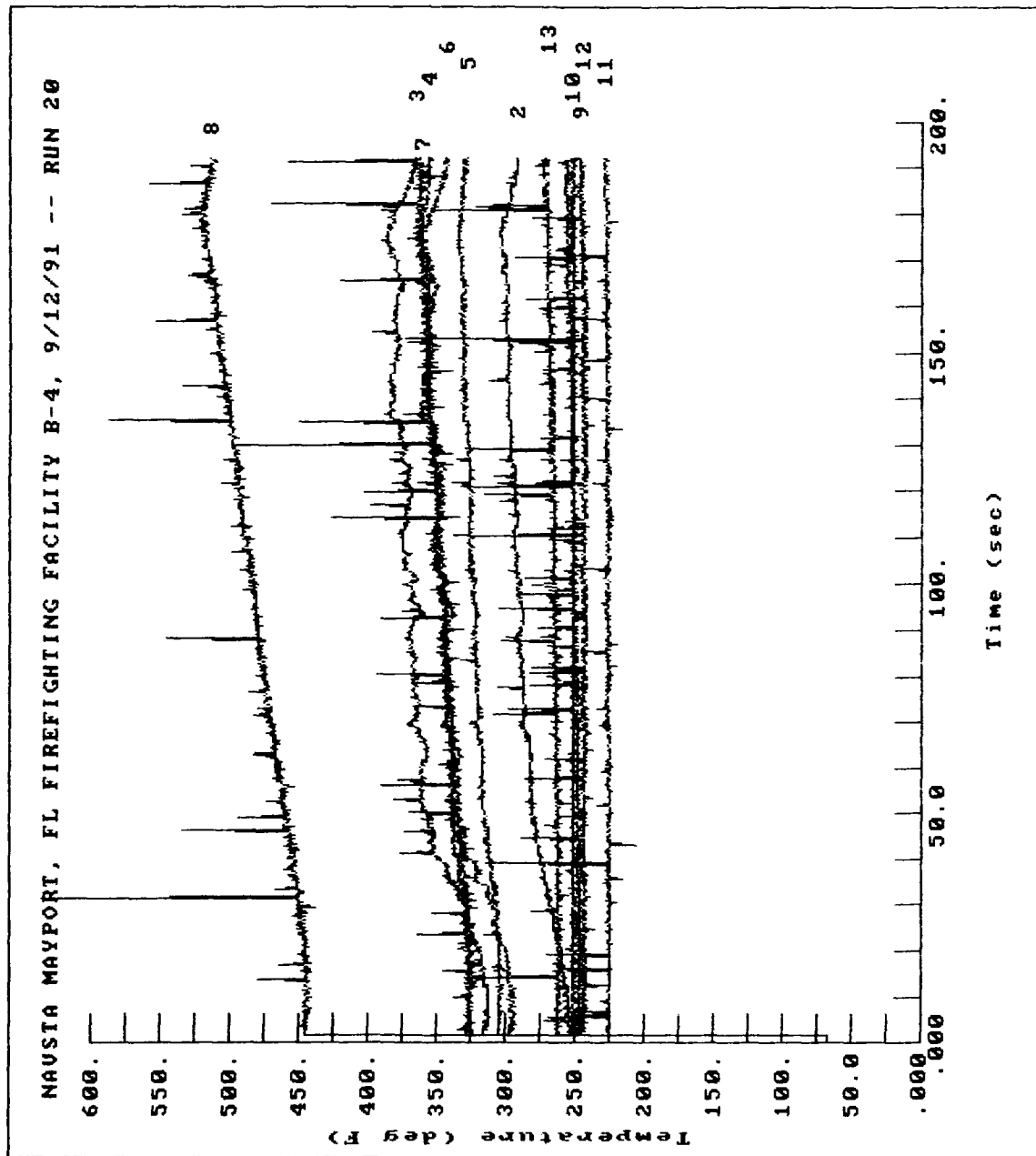


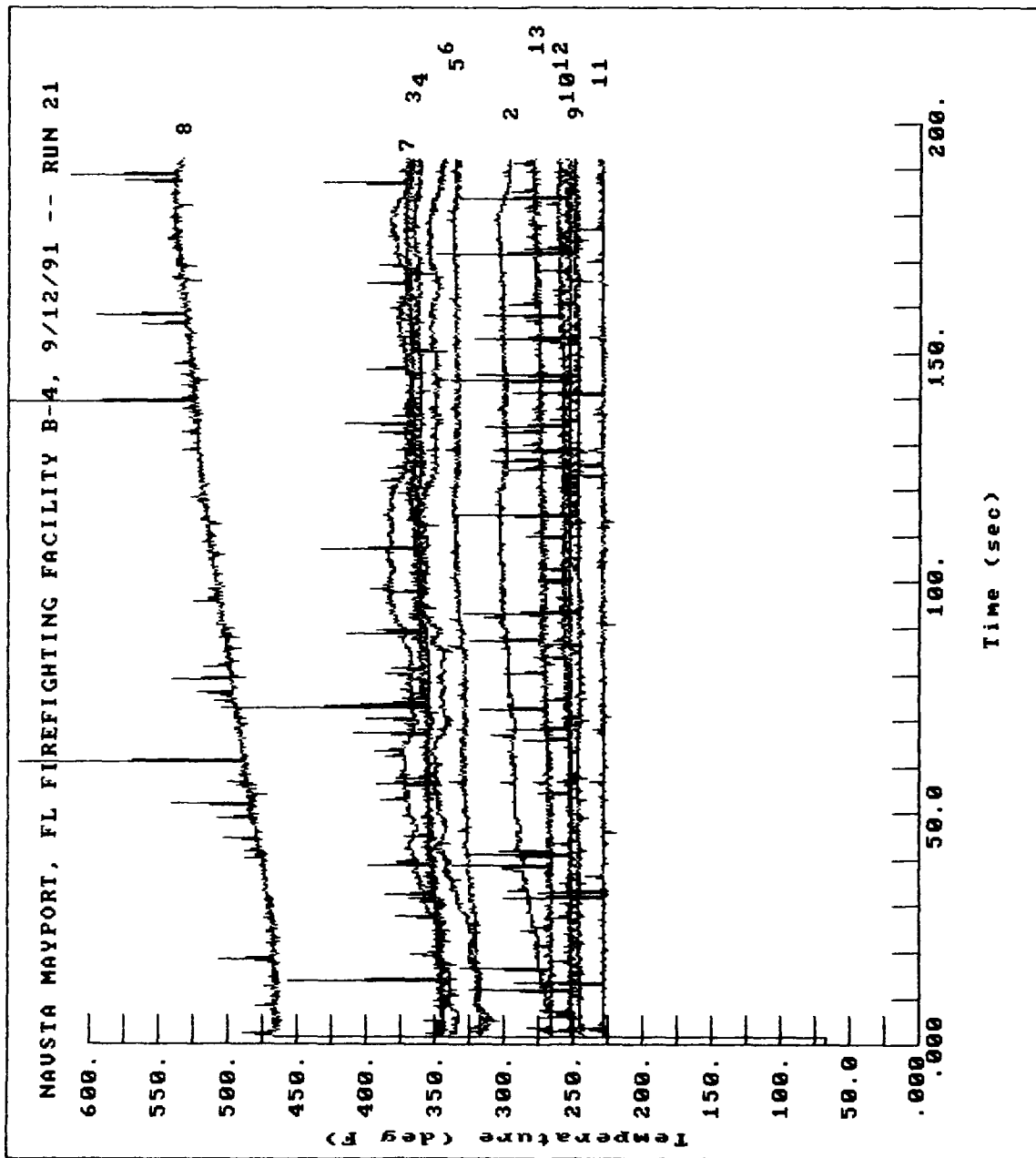


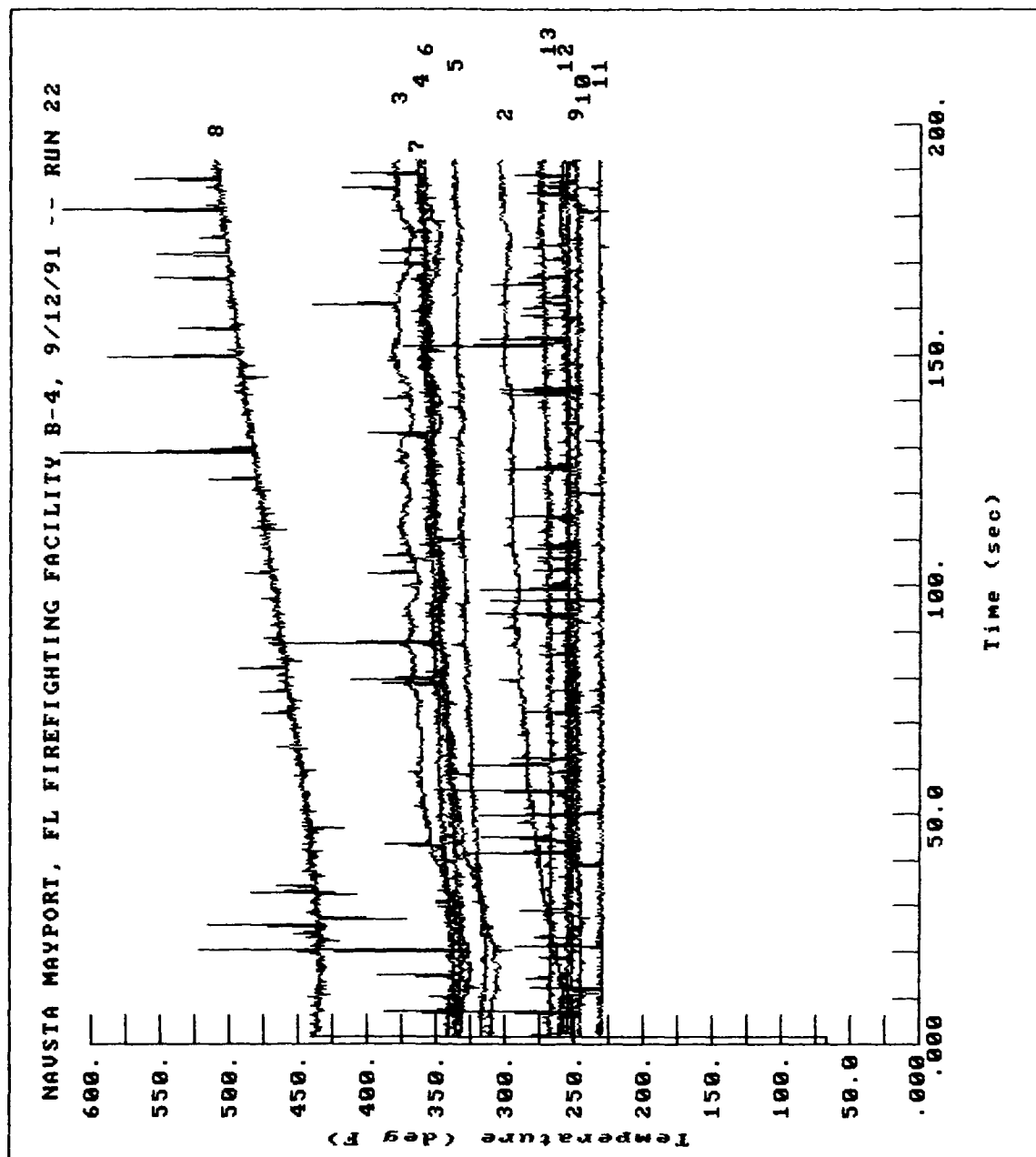


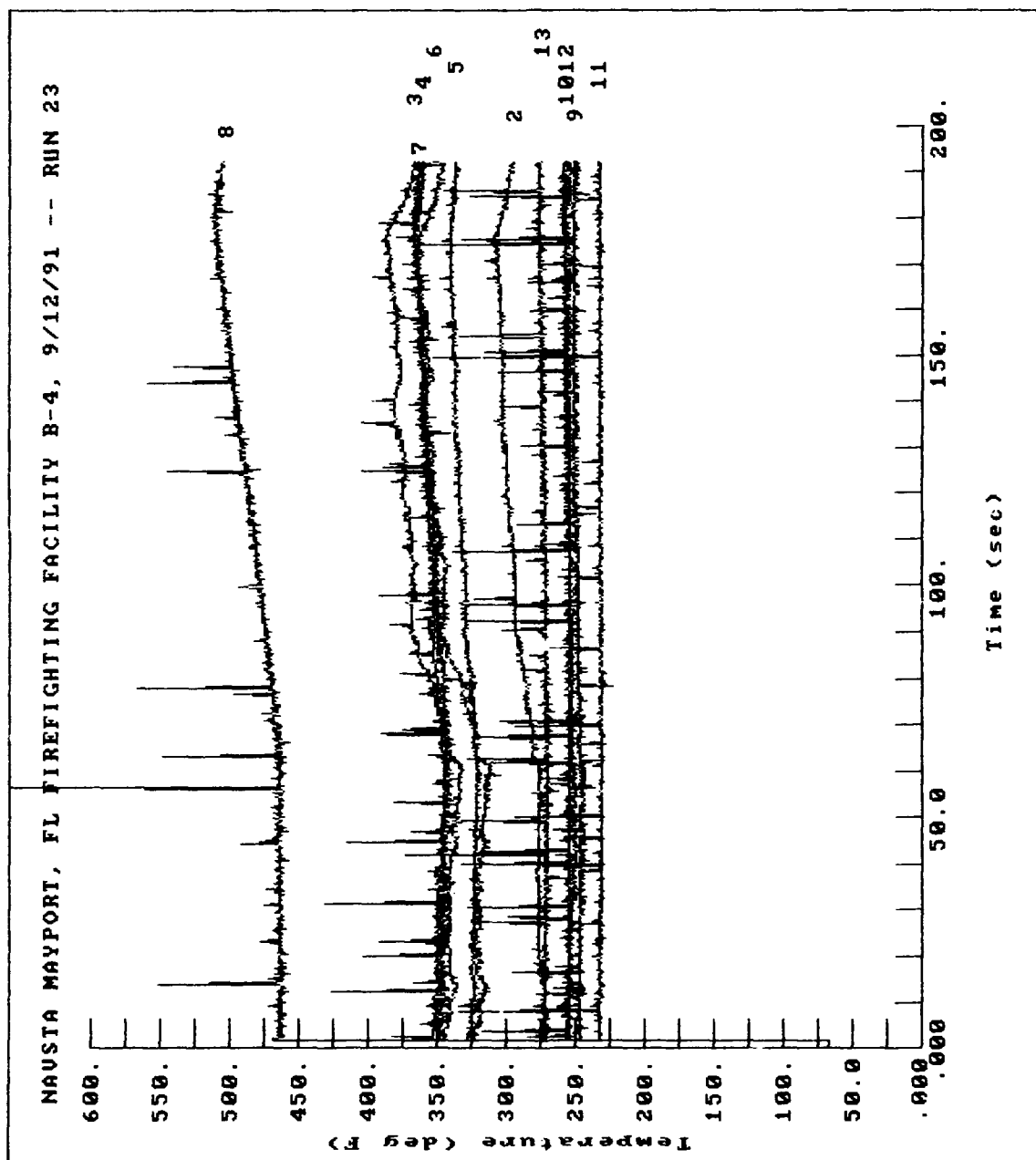


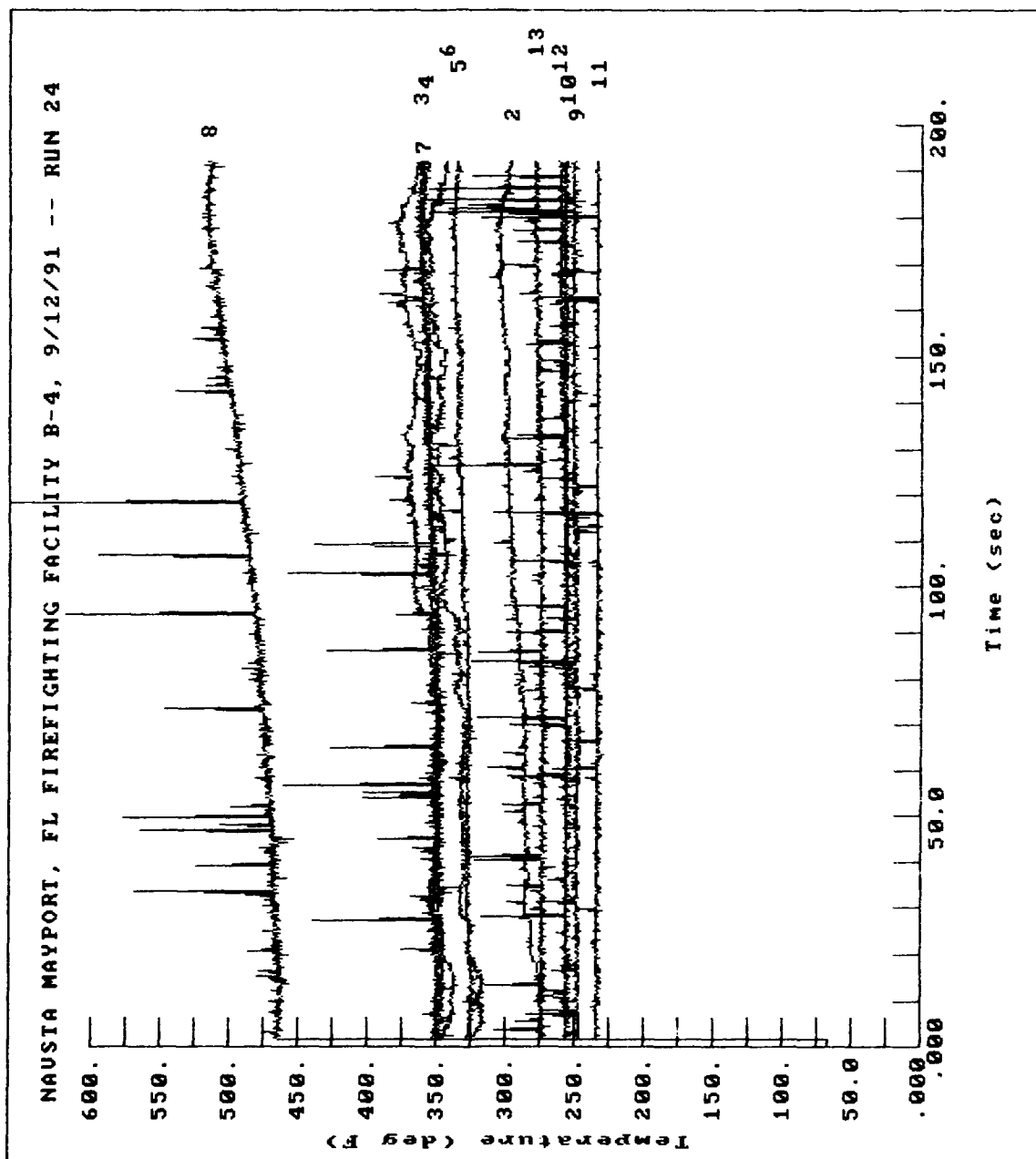


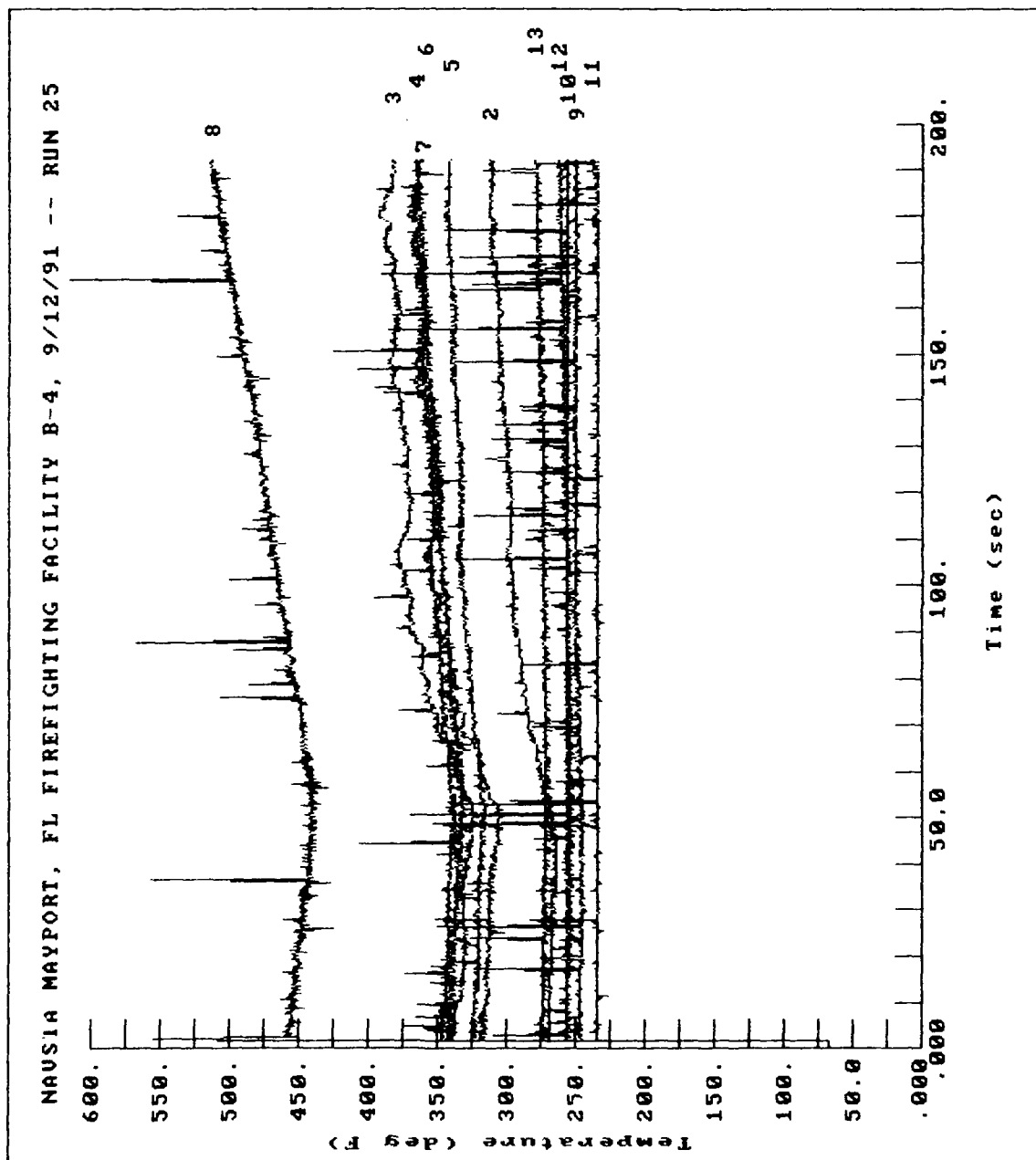


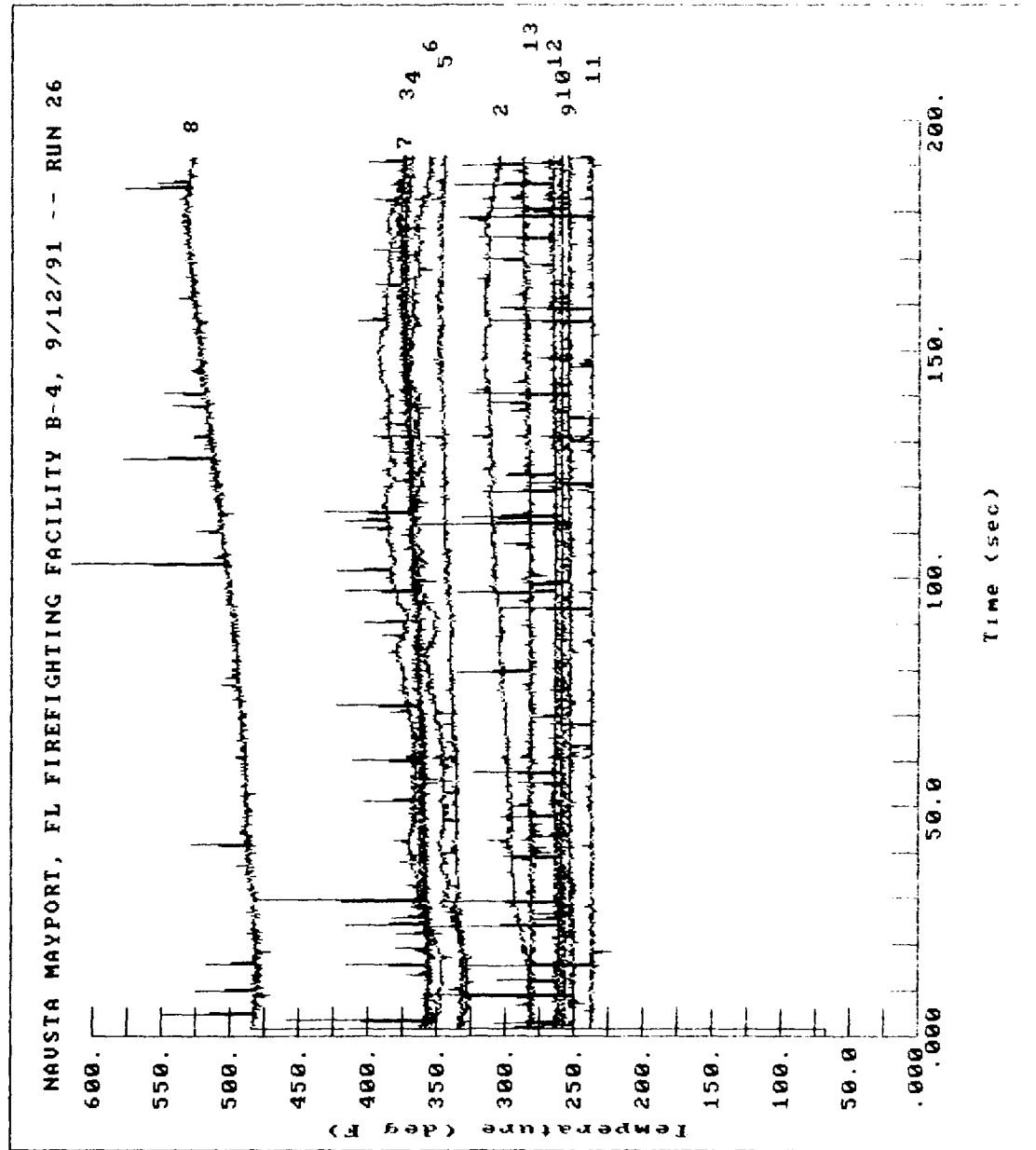




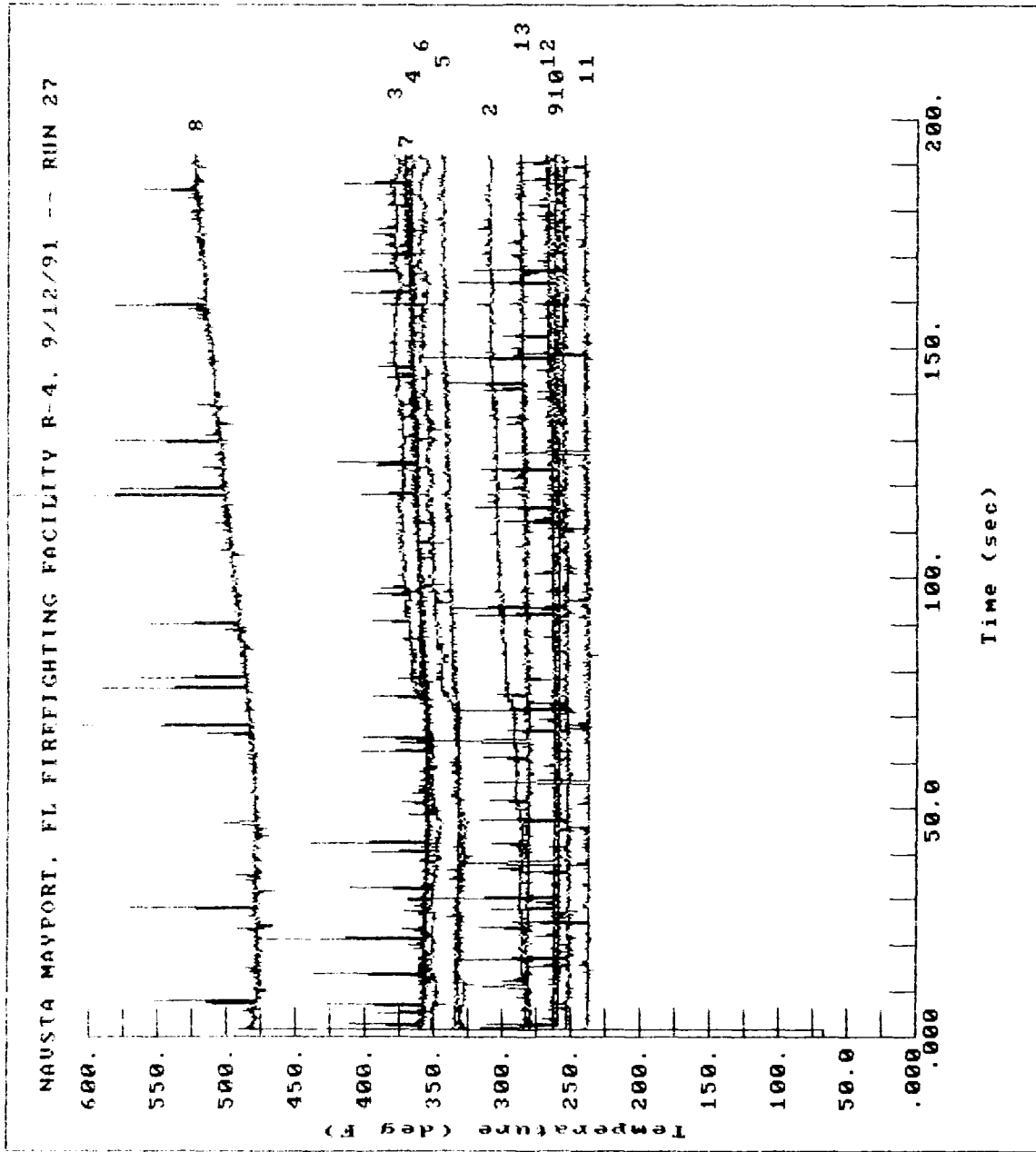


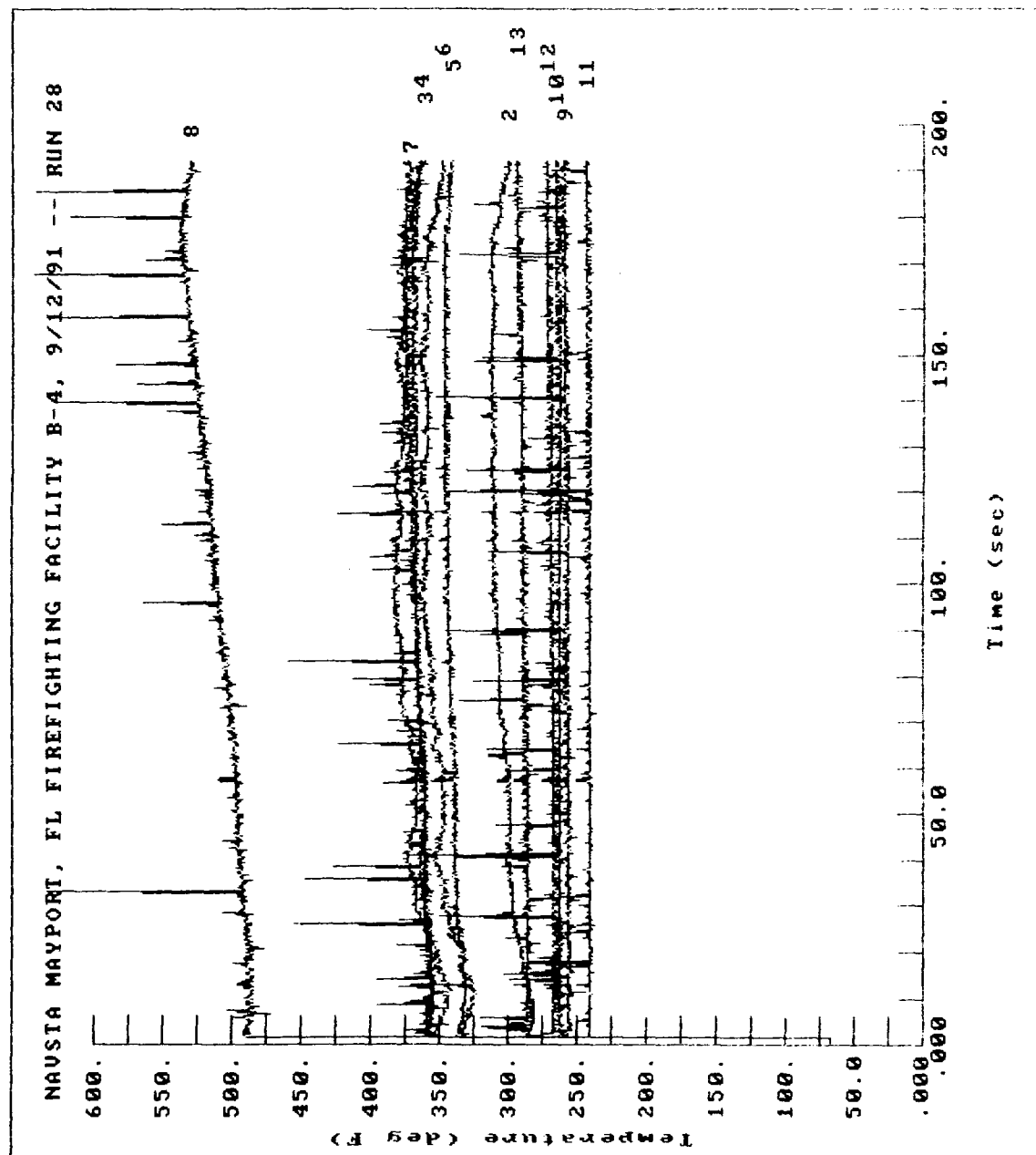












**Appendix B**

**CONTRACTOR REPORT ENTITLED,  
"PHYSICAL PROPERTY TESTS AND PETROGRAPHIC  
EXAMINATIONS OF CONCRETE CORES FROM THE  
MAYPORT FIREFIGHTING FACILITY"**

Report to

NAVAL CIVIL ENGINEERING LABORATORY  
NCEL 52559 TY9  
USNCBC, Building 599  
Port Hueneme, California 93043-5000

**PHYSICAL PROPERTY TESTS AND PETROGRAPHIC EXAMINATIONS OF  
CONCRETE CORES FROM THE MAYPORT FIRE FIGHTING FACILITY**

by

Martha G. Van Geem, P.E.

Submitted by

**CONSTRUCTION TECHNOLOGY LABORATORIES, INC.**  
5420 Old Orchard Road  
Skokie, IL 60077

050322

November 1991

# **PHYSICAL PROPERTY TESTS AND PETROGRAPHIC EXAMINATIONS OF CONCRETE CORES FROM THE MAYPORT FIRE FIGHTING FACILITY**

by

Martha G. Van Geem, P.E.\*

## **INTRODUCTION**

This test program was initiated at the request of the Naval Civil Engineering Laboratory (NCEL), Port Hueneme, California. Work was authorized by Carol A. Vernon, Supply Officer, under Contract / Purchase Order No. N6258391P7096 dated September 7, 1991. The technical contact is Mr. Doug Burke.

Construction Technology Laboratories, Inc. (CTL) received eleven concrete cores with nominal dimensions of 4 by 10 in. According to Mr. Burke of NCEL, five cores were from concrete not exposed to elevated temperatures, two cores were from concrete exposed to moderately elevated temperatures, and four cores were from concrete exposed to highly elevated temperatures. Petrographic examinations were performed on the six cores exposed to moderately and highly elevated temperatures. Physical and thermal property tests were performed on the five cores not exposed to elevated temperatures. Modulus of elasticity, compressive strength, coefficient of thermal expansion, thermal diffusivity, specific heat, and thermal conductivity were determined. According to the NCEL Statement of Work, the cores are from the Mayport Fire Fighting Facility in Mayport, Florida.

## **BACKGROUND**

The following background information is included in the NCEL Statement of Work:

NCEL has been asked to prepare a report which addresses the structural condition of building 1803 at the Fleet Training Center, Naval Station, Mayport, Florida. The building has been designed and is used to train fire fighters. Propane fires are routinely lit to simulate real fires. The Navy wishes to evaluate the condition of the

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\* Martha G. Van Geem, Senior Engineer, Construction Technology Laboratories, Inc., 5420 Old Orchard Road, Skokie, IL 60077 (708) 965-7500

concrete walls, to determine if the heat from the fires has in any way caused deterioration of the concrete. The facility has been used for about a year or two. It is expected that if any damage has occurred it will be very slight. However, even the slightest amount of deterioration is of interest to the Navy as it is desired to predict the life expectancy of the concrete under continued and long term usage.

### **OBJECTIVE AND SCOPE**

The objective and scope of the work is defined in the NCEL Statement of Work as follows:

1. Eleven concrete cores were shipped to CTL for testing and evaluation by CTL as described in Item Nos. 2 through 7.
2. Six petrographic examinations were performed in accordance with ASTM C856.
3. Modulus of elasticity was determined in accordance with ASTM C469.
4. Tests were performed to determine coefficient of thermal expansion.
5. Specific heat was determined according to U.S. Army Corps of Engineers test method CRD-C124-73.
6. Thermal diffusivity was determined according to U.S. Army Corps of Engineers test method CRD-C36-73.
7. Thermal conductivity was determined according to U.S. Army Corps of Engineers test method CRD-C44-63.

### **TEST SPECIMENS**

Eleven concrete cores with nominal dimensions of 4 by 10 in. were received at CTL on September 18, 1991. Cores were shipped by Wilkes Mechanical Contractors, 6824 Phillips Parkway Dr. S, Jacksonville, Florida, 32256. Specimens were delivered by Overnite Transportation Company.

All cores had reinforcing bars in one or two planes transverse to the longitudinal axis of the core. Generally, two perpendicular bars were observed in each plane. Cut bar diameters were approximately 5/8-in. Unless otherwise noted, the steel was left in place in all cores, and test results include the effects of the steel.

Measured core diameters were 3.7 to 3.8 in.

### **PETROGRAPHIC EXAMINATION**

Petrographic examination was performed on six concrete cores in accordance with ASTM C856-83, "Standard Practice for Petrographic Examination of Hardened Concrete." Two cores were reportedly from an area exposed to moderate heat and four cores were reportedly from an area exposed to high temperature. The concrete cores consist of siliceous lightweight coarse aggregate (expanded shale) and quartz sand in a portland cement paste.

A detailed Petrographic Services Report is attached to the end of this report.

### **MODULUS OF ELASTICITY**

Core Nos. 4 and 5 were used to determine modulus of elasticity in accordance with applicable portions of ASTM C469-87, "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression." The measured modulus of elasticity of Core No. 5 was 2,600,000 psi.

Compressive strength is determined as part of ASTM C469. The compressive strengths of Core Nos. 4 and 5 were 6540 and 6180 psi, respectively. Compressive strengths were measured in accordance with ASTM C42-87, "Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete." The core lengths were trimmed before compressive strength and modulus of elasticity tests. Trimmed lengths for Core Nos. 4 and 5 were 7.5 in. Measured core diameters were 3.7 in. Unit weights for Core Nos. 4 and 5 were 136 and 124 pcf, respectively. Test results and unit weights include the effects of steel in the cores.

### **COEFFICIENT OF THERMAL EXPANSION**

Core No. 2 was instrumented to measure longitudinal length changes to determine coefficient of thermal expansion. Gauge points were approximately 8 in. apart. Three gauge lines were placed approximately 120° apart on the outer surface of the core. Initial readings were taken at room temperature. Specimens were cooled to 50°F for 3 days, allowed to reach ambient temperature for 3 days, heated to 140°F for 5 days, and then allowed to reach room temperature for 6 days. Length changes were measured with a length comparator at the end of each time period.

The coefficient of thermal expansion is determined from the average length changes of the three gauge lines at 50 and 140°F using the following equation:

$$C = (R_h - R_c) / G \cdot \Delta T \quad (1)$$

where:

$C$  = Coefficient of linear thermal expansion, in./in. per °F

$R_h$  = Length reading at higher temperature

$R_c$  = Length reading at lower temperature

$G$  = Length between gauge points

$\Delta T$  = Difference in temperature of specimen between the two length readings, °F

The average measured coefficient of thermal expansion was 6.4 millionths in./in. per °F. This value was over a temperature range of 50 to 140°F and assumes the coefficient of thermal expansion is linear in this range. The specimen had a unit weight of 126 pcf before testing and 120 pcf after testing. The loss in unit weight is attributed to drying at 140°F. Test results and unit weights include the effects of steel in the core.

### SPECIFIC HEAT

Specific heat of material from Core No. 1 was determined in general accordance with U.S. Army Corps of Engineers CRD-C124-73, "Method of Test for Specific Heat of Aggregates, Concrete, and Other Materials (Method of Mixtures)." The actual test procedure used is included in this report as Appendix A.

The U.S. Army Corps of Engineers test method uses pieces of concrete submerged in water to determine specific heat. Generally moist-cured specimens are crushed and the material of the required size is soaked in water at least 24 hours before test. For this test, cores received were dry. Core No. 1 was crushed to obtain material of the required size and the material was soaked in room temperature water for approximately 7 weeks before testing. For purposes of determining results, it is assumed that the material from Core No. 1 was saturated at the time of test. All steel pieces were removed from the sample before testing.

The specific heat of material from Core No. 1 in a saturated state is 0.29 Btu/lb·°F. The moisture content of the material in a saturated-surface-dry (SSD) state was determined by weighing



and oven-drying the material. Assuming the material was saturated at the time of test, the SSD moisture content is 16% of the oven-dry weight.

To calculate specific heat of material in a dry state, weights of material in the particular dry state and the saturated-surface-dry state are used. The following equation is used to calculate specific heat of concrete for different moisture conditions:

$$c = \frac{c_{SSD} + \gamma(y-1)}{1 + \gamma(y-1)} \quad (2)$$

where:

$c$  = specific heat of sample at any moisture content

$c_{SSD}$  = specific heat of saturated-surface-dry sample

$y$  = moisture content expressed as a fraction of the SSD moisture content

$\gamma$  = SSD moisture content

$$\gamma = (W_{SSD} - W_{OD})/W_{SSD} \quad (3)$$

where:

$W_{SSD}$  = SSD weight of sample

$W_{OD}$  = oven-dry weight of sample

Equation 2 was used to calculate the specific heat of the material from Core No. 1 in the oven-dry and as-received moisture contents. The specific heat of the oven-dry material was 0.18 Btu/lb·°F. The as-received material was estimated to have a moisture content of 6 to 8% of its oven-dry weight and a calculated specific heat of 0.23 Btu/lb·°F.

### THERMAL DIFFUSIVITY

Thermal diffusivity of Core No. 3 was determined in accordance with U.S. Army Corps of Engineers CRD-C36-73, "Method of Test for Thermal Diffusivity of Concrete." The core was received dry and a thermocouple wire was inserted in an axially drilled hole according to the test method. The specimen had an average diameter of 3.746 in. and an average length of 10.398 in.

Measured thermal diffusivity was 0.029 ft<sup>2</sup>/hr. This test is performed with the specimen submerged in water. The moisture content of the specimen at the end of the test was 10% of the

ovendry weight. This was determined by ovendrying the specimen after testing. Since the specimen was received dry, it was probably not fully saturated at the end of the test. Test data are presented in Figure 1. Test results and unit weights include the effects of steel in the cores.

### **THERMAL CONDUCTIVITY**

Thermal conductivity was determined in accordance with U.S. Army Corps of Engineers CRD-C44-63, "Method for Calculation of Thermal Conductivity of Concrete." This test method uses measured thermal diffusivity from CRD-C36-73, measured specific heat from CRD-C124-73, and measured unit weight to calculate thermal conductivity. The values for thermal conductivity, thermal diffusivity, specific heat, and unit weight vary depending on the moisture content of the material. Therefore, when using the equation in CRD-C44-63 all properties should be stated for the same moisture content.

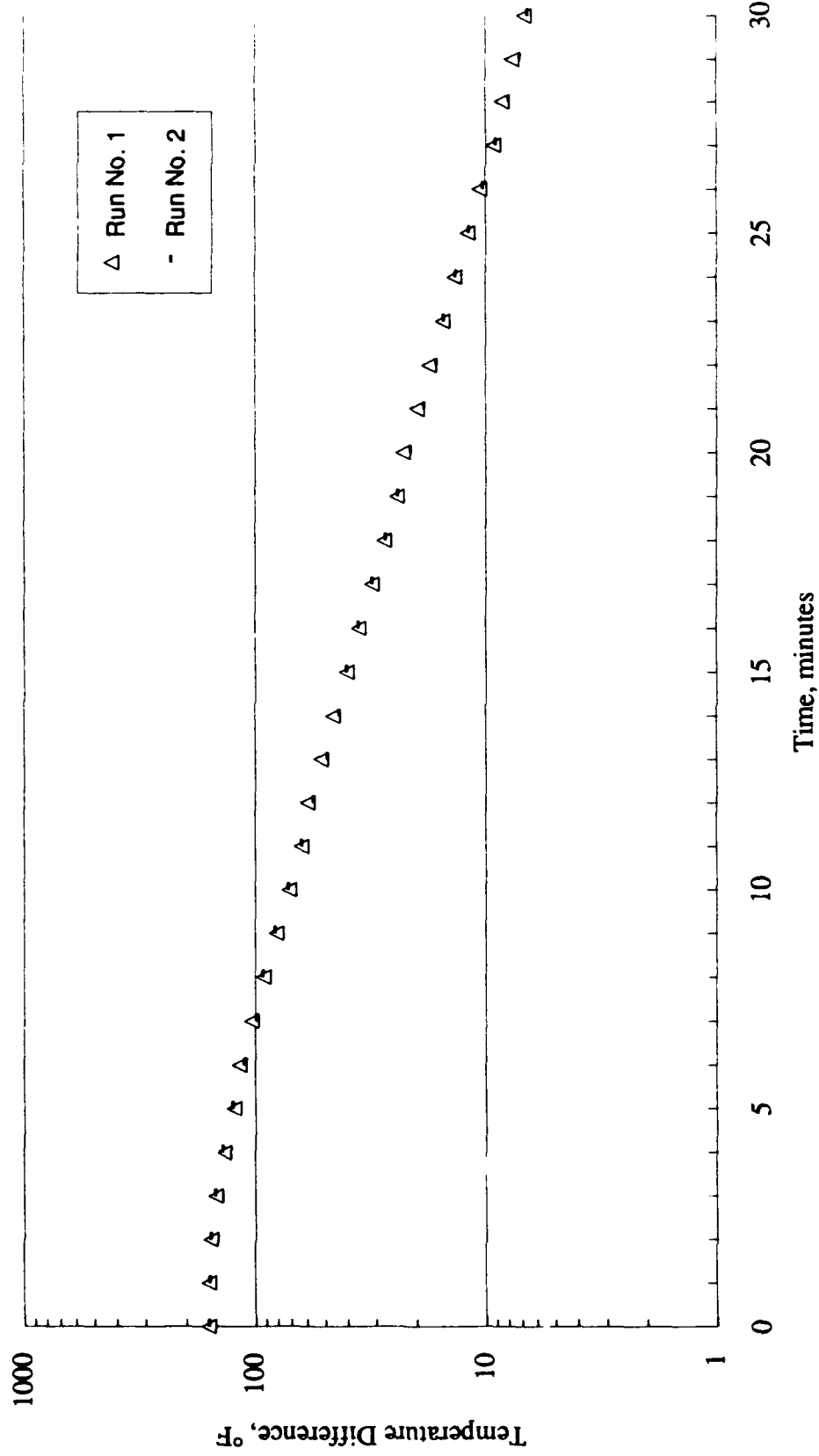
Thermal conductivity for this report is calculated at a moisture content of 10% by ovendry weight because this is the moisture content of the thermal diffusivity specimen at the end of the test. Specific heat of the concrete at a moisture content of 10% calculated using Equation 2 is 0.25 Btu/lb·°F. The unit weight of the thermal diffusivity specimen was 126 pcf after testing. The calculated thermal conductivity is 0.92 Btu/hr·ft·°F or 11.0 Btu·in./hr·ft<sup>2</sup>·°F for the concrete evaluated in this program at a moisture content of 10%. The estimated as-received moisture content of the cores is 6 to 8 % of the ovendry weight.

### **SUMMARY**

This report provides results of physical property tests and petrographic examinations on concrete cores. A detailed Petrographic Services Report is attached to the end of this report. The following findings are based on results of property tests on concrete cores:

1. The modulus of elasticity measured according to ASTM C469-87 was 2,600,000 psi.
2. The compressive strengths of two cores measured according to ASTM C42-87 were 6540 and 6180 psi.
3. The measured coefficient of thermal expansion was 6.4 millionths in./in. per °F over a temperature range from 50 to 140°F.

Fig. 1 — Thermal Diffusivity Test Results



4. The specific heat measured according to U.S. Army Corps of Engineers CRD-C124-73 was 0.29 Btu/lb·°F for concrete with a moisture content of 16% of oven-dry weight.
5. The thermal diffusivity measured according to U.S. Army Corps of Engineers CRD-C36-73 was 0.029 ft<sup>2</sup>/hr for concrete with a moisture content of 10% of oven-dry weight at the end of the test.
6. Thermal conductivity of concrete calculated according to U.S. Army Corps of Engineers CRD-C44-63 was 11.0 Btu·in./hr·ft<sup>2</sup>·°F for concrete with a moisture content of 10% of oven-dry weight.

## **APPENDIX A — SPECIFIC HEAT TEST PROCEDURE**

Method of Test for  
SPECIFIC HEAT OF AGGREGATES,  
CONCRETE, AND OTHER MATERIALS  
(Method of Mixtures)

1. Scope

1.1 This method of test covers a procedure for determining the mean specific heat ( $c$ , heat capacity) of aggregates, concrete, and other materials by the method of mixtures using particles smaller than 1 in. (25 mm) in size.

Note 1: This is a modification of CRD-C 124-73 which allows more rapid testing and eliminates some procedures found to be cumbersome and lacking in reproducibility.

2. Apparatus

2.1 The apparatus used in this test shall consist of:

2.2 Calorimeter - A calorimeter with external insulation, large enough to accommodate samples of approximately 2 lb (1 kg) in weight placed in a wire basket, and provided with an insulated cover.

2.3 Thermocouple - A thermocouple conforming to NBS IPTS-68 Type T (copper versus copper-nickel alloy), and having polyvinyl insulated lead wires.

2.4 Thermocouple Readout Device - A digital readout device (Kaye Model 6000 or equivalent) capable of transforming thermocouple (Type T) voltage into deg F over the range of 32-120°F resolvable to  $\pm 0.1^\circ\text{F}$ .

2.5 Constant-Temperature Bath, Hot - An electrically heated constant temperature bath with thermostat set at  $115 \pm 1^\circ\text{F}$  ( $46.1 \pm 0.56^\circ\text{C}$ ).

2.6 Constant-Temperature Bath, Cold - A refrigerated bath, with refrigeration thermostatically controlled at  $35 \pm 1^\circ\text{F}$  ( $1.67 \pm 0.56^\circ\text{C}$ ).

2.7 Basket - A wire-mesh basket, of material of known specific heat, approximately 4 in. (100 mm) in diameter by 4 in. (100 mm) high.

2.8 Balance - A balance capable of weighing 5 lb (2.27 kg) with an accuracy of  $\pm 0.005$  lb (2.3 g).

2.9 Standard Specimen - A specimen of material of known specific heat.

Note 2: Sapphire ( $\text{Al}_2\text{O}_3$ ) culetts having a specific heat of 0.182 Btu-lb/deg F (cal-gm/deg C) can be used.

2.10 Timer - A timer reading in minutes and seconds.

3. Specimen

3.1 For determinations of mean specific heat of aggregates, concrete, and other materials according to the method outlined herein the specimen to be used shall consist of approximately 2 lb (1 kg) of the material to be tested. The specimen shall contain no particles larger than 1 in. (25 mm) in size. When the material to be tested includes larger particles they shall be crushed before testing.

4. Procedure

Note 3: This determination need be done only when changing calorimeters or making modifications to an existing calorimeter such that its water equivalent would be changed significantly.

4.1 Determination of the Water-Equivalent of the Calorimeter - Approximately 2 lb (1 kg) of water, weighed to the nearest 0.005 lb (2 g), shall be placed in the calorimeter. The calorimeter shall be placed in the constant temperature room until temperature equilibrium is attained. A weighed specimen

specimen of known specific heat shall be placed in the wire basket, the basket shall then be suspended by a fine wire in either the hot or the cold constant-temperature bath until equilibrium is reached (about 15 min). The specimen shall have been weighed previously in a saturated-surface dry condition. The water carry-over shall be treated as described in Paragraph 5 below. The temperature of the constant-temperature bath and of the water in the calorimeter shall be recorded to 0.1°F (0.05°C), and the standard sample shall be placed inside the calorimeter. The water in the calorimeter shall be stirred by rotating the calorimeter on the desk top with a gentle circular rocking motion. Temperatures shall be recorded continuously during the temperature change, until the temperature is stable within 0.1°F (0.05°C) for approximately 2 minutes. This stable reading shall then be used in the calculations described in Paragraph 5 below.

4.2 Determination of Mean Specific Heat of Aggregates, Concrete, and Other Materials - The mean specific heat of an aggregate shall be determined by placing a weighed sample, approximately 2 lb (1 kg), in either the hot or cold water bath, and proceeding as in subparagraph 4.1. The sample shall have been weighed previously in a saturated-surface condition, and the water carry-over shall be treated in accordance with the calculations described in Paragraph 5 below. Six determinations shall be made. Hot and cold specimens shall be tested alternately, and the water in the calorimeter at the start of each test shall be replaced with fresh room temperature water.

## 5. Calculations

5.1 The water equivalent of the calorimeter and the mean specific heat of the sample of aggregate shall be calculated from the following formulas:

### 5.2 Water Equivalent -

$$M_e = \frac{(c_s M_s T + c_1 M_o T + c_b m_b T)}{c_1 T_1} - M_1$$

where:

$M_e$  = water equivalent of calorimeter, lb (gm)

$c_s$  = mean specific heat of standard, B/lb-deg F (cal/gm-deg C)

$M_1$  = weight of water placed in calorimeter, lb (gm)

$c_1$  = mean specific heat of water, B/lb-deg F (cal/gm-deg C)

**Note 4:** The specific heat of water may be assumed to be 1.000 Btu/lb-deg F (cal/gm-deg C) without significant error.

$T_1$  = temperature change of water, deg F (deg C)

$M_s$  = weight of samples, lb (gm)

$M_o$  = weight of water carry-over, lb (gm) - See test report form.

$T$  = temperature change of sample, deg F (deg C)

$c_b$  = specific heat of basket, B/lb-deg F (cal/gm-deg C)

$M_b$  = weight of basket, lb (gm)

### 5.3 Mean Specific Heat -

$$c_s = \frac{(M_1 + M_e) c_1 T_1 - (M_o c_1 + M_b c_b) T}{M_s T}$$

where:

$c_s$  = mean specific heat of specimen, B/lb-deg F (cal/gm-deg C), and the remaining symbols have the same meaning as above.



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## PETROGRAPHIC SERVICES REPORT

*CTL Project No.:* 154060

*Date:* November 11, 1991

*Re:* Microscopical Examination of Concrete from Mayport Fire Fighting Facility

Six concrete cores, labeled 6 through 11 (Figs. 1 through 3), were received on September 23, 1991 from Ms. Martha Van Geem, Senior Engineer, CTL. The samples are from the Mayport Fire Fighting Facility and were submitted on behalf of the Naval Civil Engineering Laboratory, Port Hueneme, California. Cores 6 and 7 were obtained from the west wall of the pit fire room in an area reportedly exposed to moderate heat. Cores 8, 9, 10, and 11 were taken from the east wall of the pit fire room in an area reportedly exposed to high temperature. Petrographic examination of the cores was requested to provide information related to the quality of the concrete and the depth of fire damage.

## FINDINGS AND CONCLUSIONS

Based on the results of the tests performed, the following findings and conclusions are presented:

1. The concrete cores consist of siliceous lightweight coarse aggregate (expanded shale) and quartz sand in a portland cement paste. The paste is moderately hard and the paste-aggregate bond is tight.
2. Two concretes, one light gray and the other medium gray, are observed in Cores 7, 9, 10 and 11. The concretes are identical except for water-cement ratio. The estimated water-cement ratio of the darker concrete is 0.40 to 0.50 and that of the lighter concrete is 0.50 to 0.55. The contact between the





concretes is irregular and approximately parallel to the long axis of the core. The light gray concrete is carbonated at the contact suggesting a cold joint. The two concretes are generally well-bonded.

3. The inside wall end of the cores is slightly blackened (Cores 6, 8, 9, and 10) to heavily blackened (cores 7 and 11). Carbonation and concomitant softening of the paste occurs to an average depth of 0.15 in. in Cores 6 and 7, and to a depth of 0.3 to 0.4 in. in Cores 8 through 11. Deeper carbonation (up to 1 in.) is observed around lightweight aggregate particles at the inside wall end of the core, and around cracks.
4. Cracks observed in Cores 7, 10, and 11 are oriented perpendicular to the inside wall surface, open toward the surface, and generally occur at the contact between light gray and dark gray concrete. Most cracks do not extend inward beyond 1 in.; however, a major crack in Core 10 passes through the length of the core. The crack generally separates the light gray and dark gray concretes but is observed to pass through several coarse aggregate particles.
5. No evidence of distress is observed in the concrete around the anchor bracket located in the inside wall end of Core 8. The portion of the anchor embedded in the concrete is slightly corroded and the ease of removal of the anchor indicates it is not especially well-bonded to the concrete.

Additional data from the petrographic examination are contained in the attached forms.

### **METHODS OF TEST**

Petrographic examination of the concrete cores was performed in accordance with ASTM C 856-83, "Standard Practice for Petrographic Examination of Hardened Concrete." The cores were cut longitudinally and one portion of each was lapped. Freshly broken surfaces and lapped surfaces were examined using a stereomicroscope at magnifications up to 45X. A rectangular block was cut from the inside wall end of each core to a depth of

approximately 1.8 in., placed on a glass microscope slide with epoxy resin, and reduced to a thickness of approximately 20 micrometers (0.0008 in.). The thin sections were examined using a polarized-light microscope at magnifications up to 400X to determine aggregate and paste mineralogy and microstructure.

L. J. Powers-Couche  
Associate Petrographer  
Petrographic Services

LJP-cjd

CTL

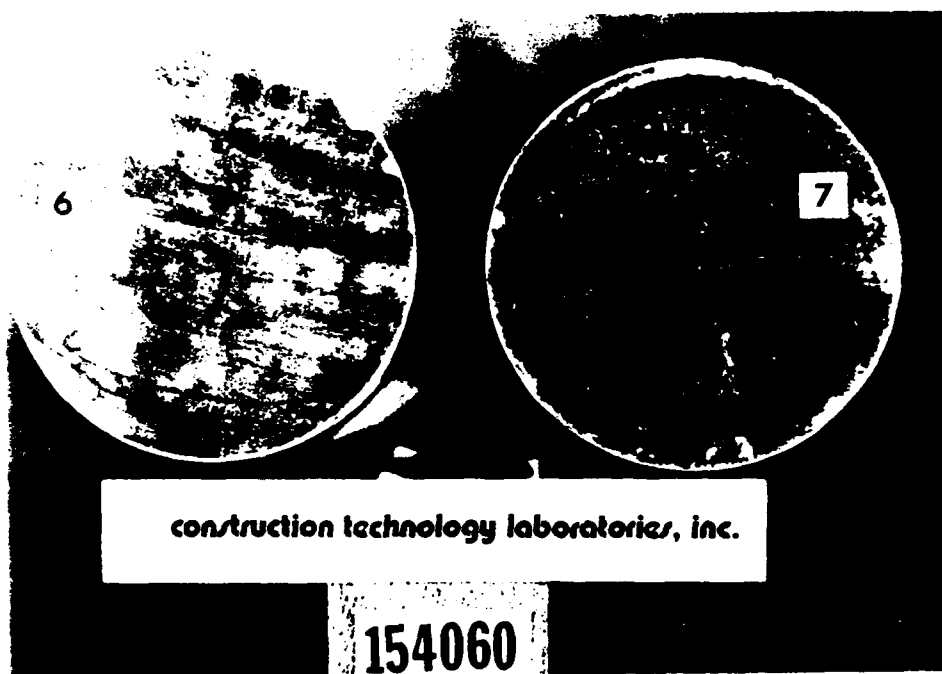


FIG. 1 INSIDE WALL SURFACE (TOP) AND SIDE VIEW (BOTTOM) OF CORES 6 AND 7 AS RECEIVED FOR EXAMINATION.

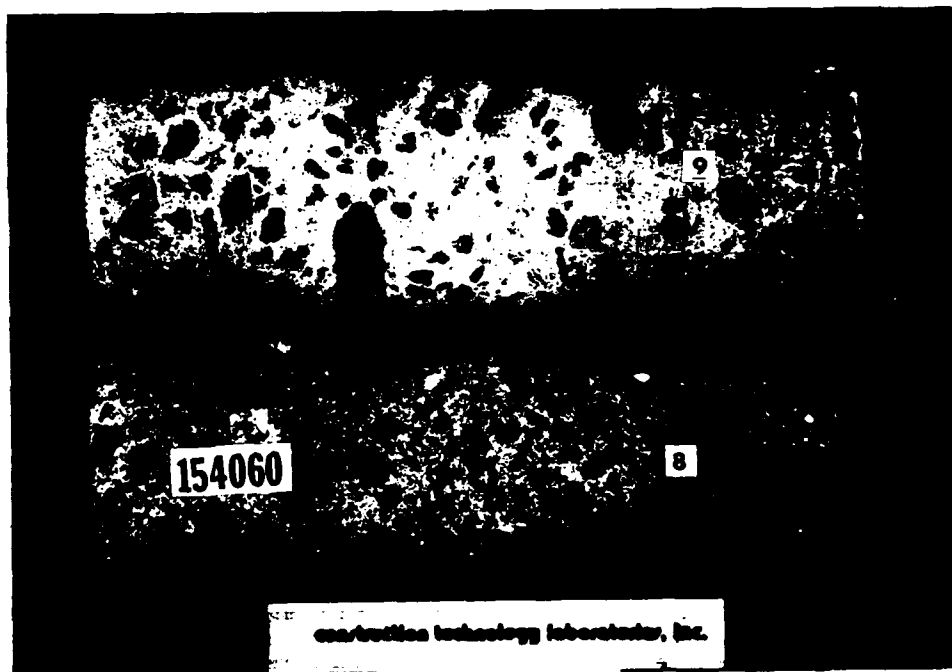
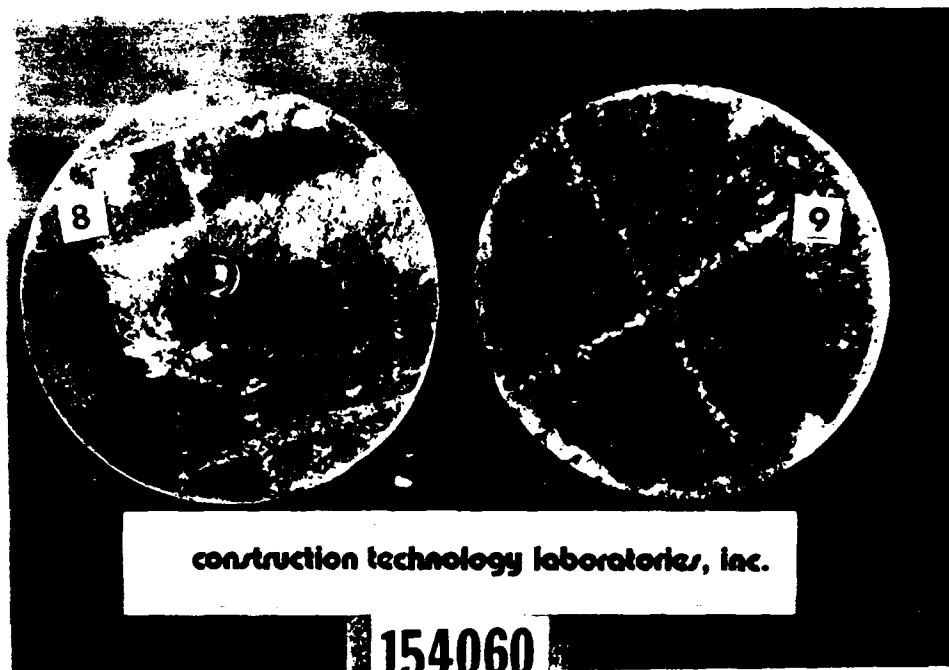


FIG. 2 INSIDE WALL SURFACE (TOP) AND SIDE VIEW (BOTTOM) OF CORES 8 AND 9 AS RECEIVED FOR EXAMINATION.

CTL

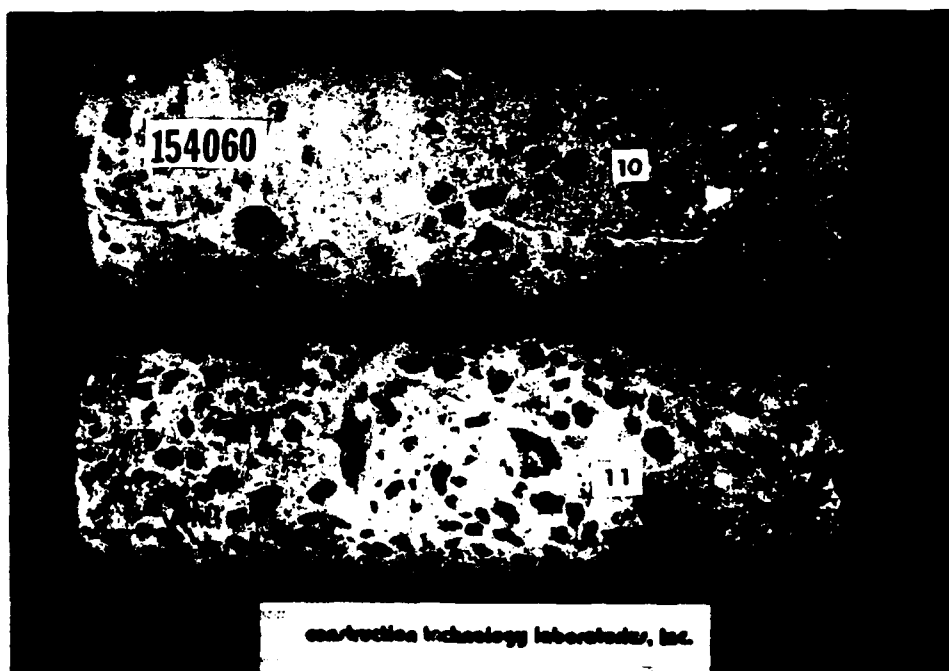
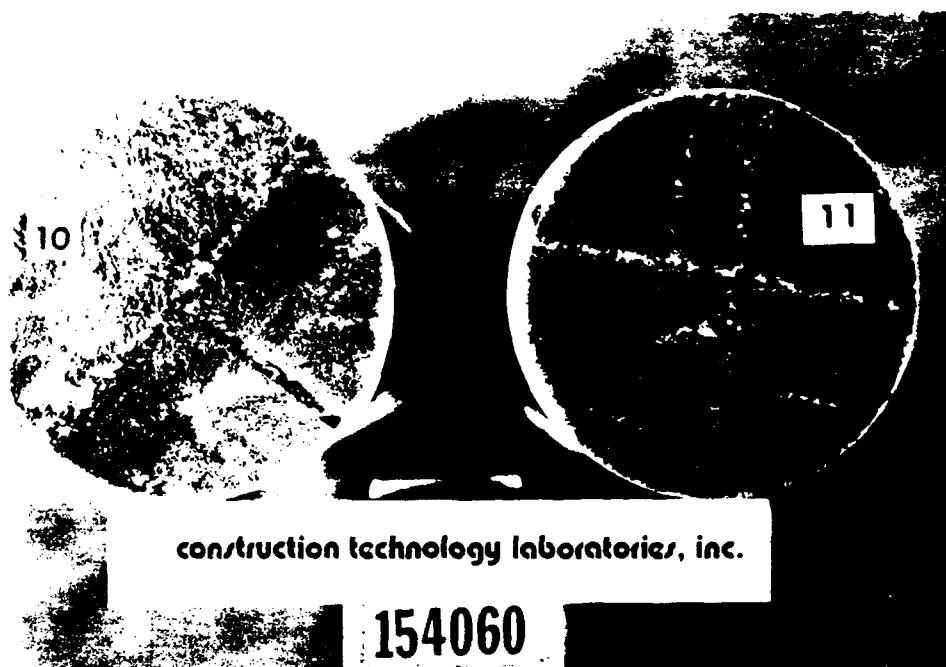


FIG. 3 INSIDE WALL SURFACE (TOP) AND SIDE VIEW (BOTTOM) OF CORES 10 AND 11 AS RECEIVED FOR EXAMINATION.

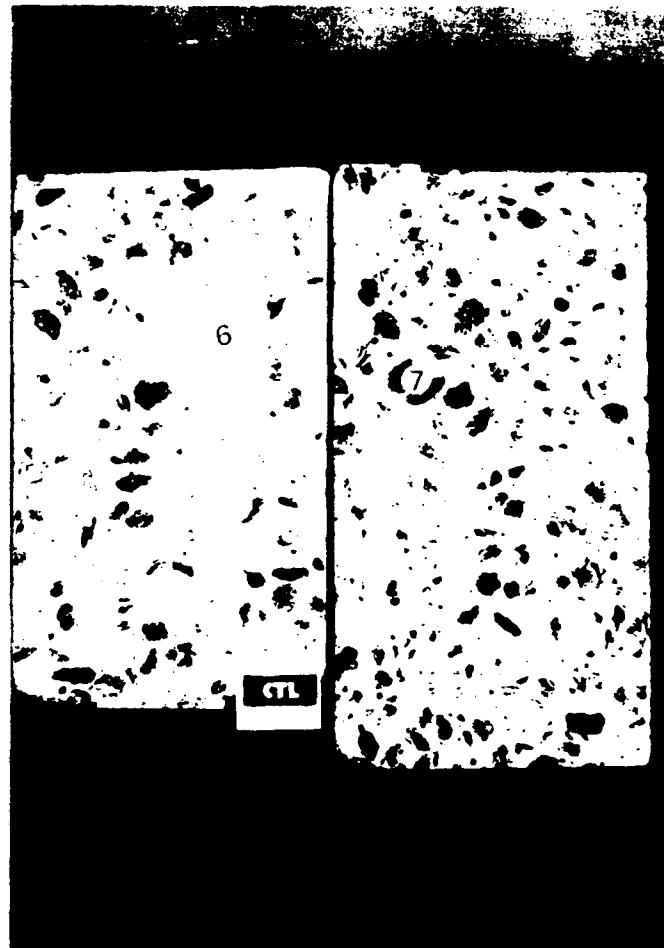


FIG. 4 LAPPED, LONGITUDINALLY SAWN SLICE THROUGH THE INSIDE WALL END OF CORES 6 AND 7. NOTE THE LARGE FOREIGN AGGREGATE IN CORE 6 (ARROW) AND AGGREGATE DISTRIBUTION. CORE 7 CONSISTS OF A LIGHT GRAY CONCRETE AND A DARKER GRAY CONCRETE. NOTE THE IRREGULAR BOUNDARY.



FIG. 5 LAPPED, LONGITUDINALLY SAWN SLICE OF THE INSIDE WALL END OF CORE 10. THE LIGHT GRAY CONCRETE IS CARBONATED NEAR THE CONTACT WITH THE DARKER CONCRETE (ARROW) AND A CRACK OR GAP OCCURS FROM THE REBAR TO THE INSIDE WALL SURFACE.

**PETROGRAPHIC EXAMINATION OF HARDENED CONCRETE, ASTM C 856**

CTL PROJECT NO.: 154060

CLIENT: Naval Civil Engineering Lab

STRUCTURE: Wall

LOCATION: Mayport Fire Fighting Facility

DATE: November 11, 1991

PROBLEM: Quality Evaluation

EXAMINED BY: L. Powers-Couche

Page 1 of 8

**SAMPLE:**

Identification: #6 West Wall ( 5 ft from floor).

Dimensions: Diameter = 3.8 in.; length = 10.0 in.

Inside Wall: Dark gray, striated surface.

Outside Wall: Smooth, painted surface.

Cracks, Joints, Large Voids: Several irregularly-shaped entrapped air voids up to 0.4 in. diameter are observed but large voids are generally rare.

Reinforcement: None observed.

**AGGREGATES (A)**

Coarse (C): Expanded shale.

Fine (F): Quartz sand.

Gradation & Top Size: Evenly graded to a top size of 0.45 in. A single 1 in.-diameter limestone fragment is observed in the sliced core.

Shape & Distribution: CA is subrounded to subangular, equidimensional to slightly elongate and somewhat nonuniformly distributed. FA is subrounded to subangular, mostly equidimensional, and uniformly distributed.

**PASTE**

Color: Medium gray.

Hardness: Moderately hard.

Luster: Subvitreous.

Calcium Hydroxide\*: 6 to 8% uniformly distributed, small crystals and coarser crystals of calcium hydroxide near aggregates and voids.

Unhydrated Portland Cement Clinker Particles (UPC's)\*: 10 to 15% uniformly distributed UPC's and voids.

Depth of Carbonation: 0.15 in. average but penetrating up to 0.5 in. around porous aggregates.

Air Content: 1 to 2% uniformly distributed, small, spherical voids and little entrapped air.

Fly Ash\*: None observed.

Paste-Aggregate Bond: Tight. The concrete breaks across the coarse aggregate particles.

Secondary Deposits: A small amount of calcium hydroxide lines voids.

Microcracking: No significant microcracks observed.

\*percent by volume of paste

**ESTIMATED WATER-CEMENT RATIO:** 0.40 to 0.45.



**PETROGRAPHIC EXAMINATION OF HARDENED CONCRETE, ASTM C 856**

CTL PROJECT NO. 154060

CLIENT: Naval Civil Engineering Lab

STRUCTURE: Wall

LOCATION: Mayport Fire Fighting Facility

DATE: November 11, 1991

PROBLEM: Quality Evaluation

EXAMINED BY: L. Powers-Couche

Page 2 of 8

**SAMPLE:**

Identification: #7 West Wall (3 ft from ceiling).

Dimensions: Diameter = 3.8 in.; length = 10.0 in.

Inside Wall: Blackened, abraded surface. A portion of the surface has a thin mortar coating.

Outside Wall: Somewhat rough, painted surface..

Cracks, Joints, Large Voids: A small number of irregularly-shaped voids up to 0.25 in. diameter are observed. One sizeable void occurs adjacent to rebar.

Reinforcement: No. 5 rebar is located 1.5 in. from the inside wall surface, and 2.3 in. from outside wall surface.

**AGGREGATES (A)**

Coarse (C): Expanded shale.

Fine (F): Quartz and quartzite.

Gradation & Top Size: Evenly graded to a top size of 0.45 in.

Shape & Distribution: CA is subrounded to angular, equidimensional to slightly elongate, and generally evenly distributed. FA is subrounded to subangular, equidimensional, and uniformly distributed.

**PASTE**

Color: Medium to pale gray.

Hardness: Moderately hard.

Luster: Subvitreous.

Calcium Hydroxide\*: 7 to 10% uniformly distributed, small crystals in paste, and patches adjacent to aggregates.

Unhydrated Portland Cement Clinker Particles (UPC's)\*: 12 to 15% UPC's and relics are uniformly distributed in the medium gray paste. The pale gray paste contains 10 to 12% uniformly distributed UPC's and relics.

Depth of Carbonation: The average depth of carbonation and buff paste color is 0.15 in. The maximum depth of carbonation, 1 in., occurs in the darker concrete where a crack 1.5 in. long separates the two concretes..

Air Content: 1 to 2% uniformly distributed, small, spherical air voids.

Fly Ash\*: None observed.

Paste-Aggregate Bond: Generally tight. The concrete breaks through aggregate particles.

Secondary Deposits: A small amount of calcium hydroxide lines voids.

Microcracking: Long, narrow microcracks are observed parallel to the junction of the two concretes. A wider crack (0.25 mm) forms part of the boundary between the concretes.

\*percent by volume of paste

**ESTIMATED WATER-CEMENT RATIO:** 0.48 to 0.55, with the medium gray concrete having the lower water-cement ratio.

**PETROGRAPHIC EXAMINATION OF HARDENED CONCRETE, ASTM C 856**

CTL PROJECT NO. 154060

CLIENT: Naval Civil Engineering Lab

STRUCTURE: Wall

LOCATION: Mayport Fire Fighting Facility

DATE: November 11, 1991

PROBLEM: Quality Evaluation

EXAMINED BY: L. Powers-Cliche

Page 3 of 8

**SAMPLE:**

Identification: #8 East Wall Center (at anchor bracket)

Dimensions: Diameter = 3.8 in.; length = 10.3 in.

Inside Wall: Somewhat rough, blackened surface with projecting anchor. The surface has a thin mortar coating.

Outside Wall: Smooth, painted surface with a large rough patch of mortar.

Cracks, Joints, Large Voids: None observed.

Reinforcement: Anchor bracket projects from inside wall surface.

**AGGREGATES (A)**

Coarse (C): Expanded shale.

Fine (F): Quartz sand.

Gradation & Top Size: Evenly graded to a top size of 0.5 in.

Shape & Distribution: CA is subrounded to subangular, equidimensional to slightly elongate and somewhat nonuniformly distributed. FA is subrounded to subangular, mostly equidimensional, and uniformly distributed.

**PASTE**

Color: Medium gray.

Hardness: Moderately hard.

Luster: Subvitreous.

Calcium Hydroxide\*: 7 to 10% uniformly distributed, small crystals, coarse patches, and partial fringes on aggregates.

Unhydrated Portland Cement Clinker Particles (UPC's)\*: 10 to 15% uniformly distributed UPC's and relict

Depth of Carbonation: Average depth is 0.3 in..

Air Content: 1 to 2% nonuniformly distributed, small, spherical air voids and small amount of entrapped air. Voids are somewhat clustered.

Fly Ash\*: None observed.

Paste-Aggregate Bond: Tight. The concrete breaks across the coarse aggregate particles.

Secondary Deposits: A small amount of ettringite lines voids.

Microcracking: No significant microcracks are observed.

\*percent by volume of paste

**ESTIMATED WATER-CEMENT RATIO:** 0.45 to 0.50.

**MISCELLANEOUS:** The steel anchor is 3.25 in. long. No deterioration is observed on the inner wall surface. The steel is somewhat corroded within the concrete and the bond between the anchor and the concrete is not especially strong.

**PETROGRAPHIC EXAMINATION OF HARDENED CONCRETE, ASTM C 856**

*CTL PROJECT NO.:* 154060

*CLIENT:* Naval Civil Engineering Lab

*STRUCTURE:* Wall

*LOCATION:* Mayport Fire Fighting Facility

*DATE:* November 11, 1991

*PROBLEM:* Quality Evaluation

*EXAMINED BY:* L. Powers-Couche

Page 4 of 8

**SAMPLE:**

**Identification:** #9 East Wall Center (to right of 8).

**Dimensions:** Diameter = 3.8 in.; length = 10.6 in.

**Inside Wall:** Somewhat rough, blackened surface.

**Outside Wall:** Generally smooth, painted surface.

**Cracks, Joints, Large Voids:** The core intersected what appeared to be a cold joint, or construction artifact, between medium gray concrete and pale gray to buff concrete. Some of the latter is underconsolidated, especially from the outside wall rebar to within 0.5 in. of the inside wall surface. Wood fragments are incorporated in the concrete near the inside wall surface at the contact between the two concretes..

**Reinforcement:** No. 5 rebar is 2.9 in. from outside wall surface.

**AGGREGATES (A)**

**Coarse (C):** Expanded shale.

**Fine (F):** Quartz and quartzite.

**Gradation & Top Size:** Evenly graded to a top size of 0.45 in.

**Shape & Distribution:** CA is subrounded to subangular, equidimensional to slightly elongate, and generally evenly distributed. FA is subrounded to subangular, equidimensional, and uniformly distributed.

**PASTE**

**Color:** Medium gray. Only a small portion of the light gray concrete was intersected.

**Hardness:** Moderately hard.

**Luster:** Subvitreous.

**Calcium Hydroxide\*:** 6 to 8% uniformly distributed small crystals and coarse patches.

**Unhydrated Portland Cement Clinker Particles (UPC's)\*:** 10 to 15% uniformly distributed UPC's and relics.

**Depth of Carbonation:** Up to 1.0 in the underconsolidated concrete; average depth of carbonation in the medium gray concrete is 0.5 in. from the inside wall.

**Air Content:** 1 to 2% uniformly distributed, small, spherical air voids.

**Fly Ash\*:** None observed.

**Paste-Aggregate Bond.** Generally tight. The concrete breaks through aggregate particles.

**Secondary Deposits.** A small amount of calcium hydroxide lines voids.

**Microcracking:** No significant microcracking is observed.

---

\*percent by volume of paste

ESTIMATED WATER-CEMENT RATIO: 0.45 to 0.50.

MISCELLANEOUS: The paste is carbonated around coarse aggregate particles near the inside wall.

**PETROGRAPHIC EXAMINATION OF HARDENED CONCRETE, ASTM C 856**

CTL PROJECT NO.: 154060

CLIENT: Naval Civil Engineering Lab

STRUCTURE: Wall

LOCATION: Mayport Fire Fighting Facility

DATE: November 11, 1991

PROBLEM: Quality Evaluation

EXAMINED BY: L. Powers-Couche

Page 6 of 8

**SAMPLE:**

**Identification:** #10 East Wall Center (12 ft).

**Dimensions:** Diameter = 3.8 in.; length = 10.2 in.

**Inside Wall:** Rough, abraded, blackened surface with a thin mortar topping.

**Outside Wall:** Smooth, painted surface.

**Cracks, Joints, Large Voids:** Crack trace 0.016 in. wide on top surface occurs at the boundary of a light gray and a medium gray concrete, presumably, representing different placements. The crack runs the length of the core and the lighter concrete is carbonated within 0.1 in. of the contact. The darker concrete is slightly carbonated. The crack passes through coarse aggregates..

**Reinforcement:** No. 5 rebar is located 2.0 in. from the inside wall surface.

**AGGREGATES (A)**

**Coarse (C):** Expanded shale.

**Fine (F):** Quartz and quartzite.

**Gradation & Top Size:** Evenly graded to a top size of 0.5 in.

**Shape & Distribution:** CA and FA are subrounded to subangular, equidimensional to slightly elongate, and generally uniformly distributed.

**PASTE**

**Color:** Medium gray to light gray.

**Hardness:** Moderately hard.

**Luster:** Subvitreous.

**Calcium Hydroxide\*:** 7 to 10% nonuniformly distributed calcium hydroxide in the medium gray concrete occurs in patches. 10 to 12% calcium hydroxide in the light gray concrete occurs as nonuniformly distributed bladed crystals, patches, and partial fringes on aggregate particles.

**Unhydrated Portland Cement Clinker Particles (UPC's)\*:** 10 to 15% nonuniformly distributed UPC's and relics.

**Depth of Carbonation:** 0.3 in. from inside wall surface. 0.1 in. carbonation at boundary of light gray concrete and medium gray concrete.

**Air Content:** 2 to 4% small, spherical, somewhat clustered air voids.

**Fly Ash\*:** None observed.

**Paste-Aggregate Bond:** Tight. The concrete breaks across the aggregate particles.

**Secondary Deposits:** Ettringite needles line or fill voids in both the light gray and medium gray concrete. A small amount of coarse, tabular calcium hydroxide partially fills voids.

**Microcracking:** Microcracks in the inside wall portion of the concrete occur in the outer 0.1 in. and are parallel to wall surface.

\*percent by volume of paste

ESTIMATED WATER-CEMENT RATIO: 0.45 to 0.50 medium gray concrete; 0.50 to 0.55 light gray concrete.

MISCELLANEOUS: On the inside wall end of the core, the paste is leached of calcium hydroxide from the surface inward to 0.5 in.

**PETROGRAPHIC EXAMINATION OF HARDENED CONCRETE, ASTM C 856**

CTL PROJECT NO 154060

CLIENT: Naval Civil Engineering Lab

STRUCTURE: Wall

LOCATION: Mayport Fire Fighting Facility

DATE: November 11, 1991

PROBLEM: Quality Evaluation

EXAMINED BY: L. Powers-Couche

Page 8 of 8

**SAMPLE:**

Identification: #11 East Wall Center (top).

Dimensions: Diameter = 3.8 in.; length = 10.2 in.

Inside Wall: Somewhat rough, blackened surface with a dark gray mortar topping up to 0.2 in. thick.

Outside Wall: Somewhat rough, painted surface. A thin mortar coating covers a portion of the outside wall surface.

Cracks, Joints, Large Voids: The core intersected an area of medium gray concrete near the inside wall end of the core. The concrete contains oval entrapped air voids up to 0.4 in. diameter.

Reinforcement: No. 5 rebar is located 2.1 in. from outside wall surface.

**AGGREGATES (A)**

Coarse (C): Expanded shale.

Fine (F): Quartz sand.

Gradation & Top Size: Evenly graded to a top size of 0.45 in.

Shape & Distribution: CA is subrounded to subangular, equidimensional to slightly elongate, and somewhat nonuniformly distributed. FA is subrounded to subangular, mostly equidimensional, and uniformly distributed.

**PASTE**

Color: Small area of medium gray paste. Bulk of sample is pale gray.

Hardness: Moderately hard.

Luster: Subvitreous to dull.

Calcium Hydroxide\*: 8 to 12% nonuniformly distributed calcium hydroxide occurs as small crystals and coarse patches in the paste, and partial fringes around aggregate particles.

Unhydrated Portland Cement Clinker Particles (UPC's)\*: 10 to 15% nonuniformly distributed UPC's and relics.

Depth of Carbonation: 0.1 to 0.4 in. soft, buff, carbonated paste.

Air Content: 1 to 2% generally uniformly distributed, small, spherical air voids.

Fly Ash\*: None observed.

Paste-Aggregate Bond: Tight.

Secondary Deposits: Ettringite needles and calcium hydroxide blades line or fill most voids.

Microcracking: Cracks occurring in the inner 0.2 in. (inside wall) are generally parallel to the surface. A few perpendicular cracks in the inside wall end of the core pass through aggregates and are typically limited to a depth of 0.25 in.

---

\*percent by volume of paste

**ESTIMATED WATER-CEMENT RATIO:** 0.50 to 0.55.

**MISCELLANEOUS:** A gap occurs between the mortar topping and the concrete.

## Appendix C

### RECOMMENDED SPECIFICATION CHANGES FOR HEAT RESISTANT CONCRETE TO BE USED IN FIREFIGHTING FACILITIES

#### 1.0 MATERIALS

##### 1.1 Cement

Use ASTM C 150 or ASTM C 595. Follow ACI 225R-85 to select a cement to use.

##### 1.2 Water

Fresh, clean, and potable.

##### 1.3 Aggregates

All aggregates to be used in a specific mix design shall meet the following criteria:

a. Both coarse and fine aggregate shall be:

(1) Manufactured from the same original material and therefore of the same physical and chemical composition. The only difference shall be the aggregate size.

(2) Classified as structural lightweight aggregate as defined in ACI 213R-87, Figure 1.4. The following are example candidate aggregates for use in mix designs:

<u>Aggregate</u>	<u>Source (example)</u>
Arkalite	Arkansas Lightweight Aggregate Corporation P.O. Box 1567-Highway 147 West Memphis, AK 72303
Solite	Solite Corporation Box 27211 Richmond, VA 23261

(3) Shall not contain any foreign material that may have a deleterious effect on the finished concrete.

(4) Maximum coarse aggregate size shall not be greater than 3/8 inch.



### **1.3.1 Fine Lightweight Aggregate**

- a. Fine lightweight aggregate shall be identical in chemical composition as the coarse aggregate and shall have been manufactured specifically for use in structural lightweight concrete. The only difference is the size of the particles.
- b. The gradation shall be proper with 85 to 100 percent passing the Number 4 sieve.
- c. Deleterious substances (e.g., foreign material and dust particles) shall not be included.
- d. Meets all other requirements of ASTM C 330.

### **1.3.2 Coarse Lightweight Aggregate**

- a. The coarse lightweight aggregate shall be identical in chemical composition as the fine aggregate to be used and shall have been manufactured specifically for use in structural lightweight concrete. The only difference is the size of the particles.
- b. The gradation shall be proper and the maximum coarse aggregate size shall be no greater than 3/8 inch, preferably less.
- c. Deleterious substances (e.g., foreign material and dust particles) shall not be included.
- d. Meets all other requirements of ASTM C 330.

## **1.4 Admixtures**

See ACI 212.1R and ACI 212.2R for guidance on the use of admixtures.

## **2.0 CONCRETE MIX DESIGN**

### **2.1 Procedure**

a. Mix design shall be conducted in accordance with ACI 211.2-81. Both coarse and fine aggregate shall be classified as lightweight such that the resulting concrete qualifies as "all lightweight."

- b. Conduct mix design on candidate aggregates and test properties.

### **2.2 Properties**

- a. Concrete shall conform to the following:

Unit Weight: less than 120 pcf (preferably 90 to 100 pcf).

Minimum Compressive Strength: 8,000 psi.

Minimum Flexural Strength at 28 days: 650 psi.

Minimum Tensile Strength at 28 days: 460 psi.

Maximum Aggregate Size: 3/8 inch.

Slump: Use the lowest value in which placing, consolidating, and finishing can be satisfactorily achieved. Maximum slump should be limited to less than 4 inches.  
(Caution: Excessive slump will result in coarse aggregate segregating up to the surface.)

Entrained Air Content: 5 to 9 percent (by volume).

Water-Cement Ratio: Less than 0.4. Evaluate each mix design by assessing cement content and slump.

Cement Content: To be determined through mix designs.

Suggested initial trial cement content: 8 to 10 sacks/yd<sup>3</sup>  
(725 to 940 lb/yd<sup>3</sup>).

**b. Optimum Thermal Properties:**

Coefficient of Thermal Expansion: 3 to 4 ppm/°F (or less).

Specific Heat: 0.009 Btu/(in.<sup>3</sup> · °F) at 0°F (or less).  
0.013 Btu/(in.<sup>3</sup> · °F) at 400°F (or less).

Conductivity: 0.025 Btu · in./h · (in.<sup>2</sup> · °F) (or more).

**2.3 Mix Design Selection Criteria**

a. The mix design that has the lowest values of coefficient of thermal expansion, unit weight, and specific heat and the highest value of conductivity will provide the highest resistance of thermal fatigue.

**b. Selection Procedure:**

(1) Rank mix designs according to desired thermal properties.  
(Note that conductivity is ranked in the inverse order as the other three parameters.)

(2) Assign weighting values as follows:

2 each for coefficient of thermal expansion and unit weight.

1 each for specific heat and conductivity.

- (3) Multiply the weighting factor times the rank and sum the results for each mix design.
- (4) Select the mix design that has the lowest score.

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